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LIMITING VALUES OF GRAVITATIONAL AND MAGNETIC ANOMALIES DUE TO A SUBTERRANEAN STRUCTURE BOUNDED BY A SINGLE DIFFERENTIAL SURFACE*

J. W. FISHER†

ABSTRACT

Calculations are made of gravitational and magnetic anomalies supposed due to local variations in the form of a single differential surface separating an overlying rock from an underlying one, the effective thickness of the latter being infinite. Both layers are homogeneous in density or magnetic susceptibility and only those magnetic effects are considered which are due to induction in the earth's magnetic field.

The maximum possible values of these anomalies and of their first and second horizontal derivatives are calculated under these simplified conditions, and it is pointed out that the numerical readings of these quantities, provided by survey results, may lead to useful estimates of the extreme depth and proportions of the structure responsible.

A fundamental problem of geophysics is that of deducing from surface measurements of the gravitational and magnetic fields at various points over a given region and kind of underground rock, structures which may account for the observed variations from normal. One of the simplest assumptions we might be permitted to make in certain cases is that the observed surface anomalies may be accounted for by projections of an underlying basement rock into an overlying one, each of the two layers being assumed homogeneous in density and magnetic susceptibility and the lower of the two supposed to extend downwards to an infinite depth. Even with such simplifying assumptions, the problem of determining the form of the boundary surface separating the two layers, so as to fit in with the observed surface fields, may be very difficult and tedious to solve, depending as it

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† Geophysical Department, Anglo-Iranian Oil Co., Ltd.

does to a large extent on trial and error. In a previous paper,[1] an experimental method of computation has been described which might assist in this process. However, in certain practical cases, all that may be required of the survey is an estimate of the depth of the upper surface of the basement layer and the vertical extent of the folds in its bounding surface. Now it can be shown that, whatever the nature of the folding of the differential surface separating the two layers of rock, there will be certain maximum possible values for the anomalies

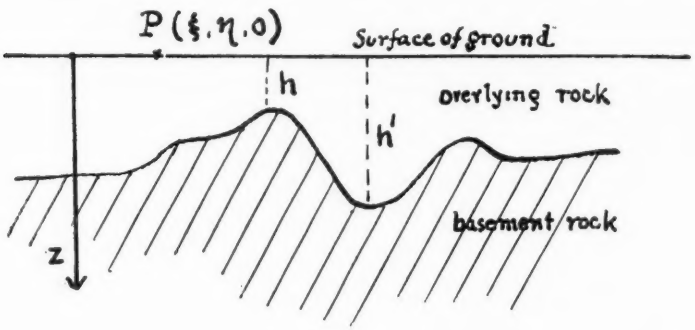

FIG. 1

and their horizontal derivatives on the surface of the ground, and that these limiting values will depend solely on the assumed difference in density or susceptibility, and on the greatest and least depths of the bounding surface below the surface of the ground. A knowledge of these theoretical maxima enables us alternatively, by comparison with the maximum observed values of the corresponding quantities, to fix certain limits to the depth of the bounding surface. An upper limit, for instance, for the shallowest depth can be found from the maximum observed value of the second and higher horizontal derivatives of the vertical gravity anomaly or from the first and higher horizontal derivatives of the vertical magnetic anomaly. The geometrical form of those structures of the bounding surface which would lead to these theoretical maxima are often widely different than any which might be expected as approximations to actual geological structures, but the existence of such absolute limits is none the less important on that account. These limiting values will now be calculated in order, starting with the gravitational anomaly.

[1] J. W. Fisher: GEOPHYSICS, Vol. 5, No. 1, Jan. 1940.

The density excess of the basement layer over that of the surface layer will be denoted by ρ, assumed to be positive. The corresponding relative magnetic susceptibility will be denoted by k. The structure of the boundary surface is supposed confined between two horizontal planes, the upper of which is at a depth h and the lower at a depth h' below the surface, which is taken as the xy plane, the z axis being supposed vertically downwards (Fig. 1.).

A. VERTICAL GRAVITATIONAL ANOMALY

Consider a layer of vertical thickness Δz at a depth z. An element of matter of area $dxdy$ at a point (x,y,z) of this layer will, if occupied by basement rock, contribute to the vertical gravitational force at a surface point P (ξ,η,o) an amount

$$G\rho z\Delta z dxdy/[z^2 + (x - \xi)^2 + (y - \eta)^2]^{3/2},$$

where G is the gravitational constant. Since z is always positive, this contribution must always be positive. The contribution of the whole layer at depth z to the vertical gravitational anomaly at the surface point P is

$$\Delta(\delta g_z) = G\rho\Delta z \iint \frac{z dxdy}{[z^2 + (x - \xi)^2 + (y - \eta)^2]^{3/2}}, \qquad (1)$$

and the maximum effect at P will be obtained by filling up all the space between $z=h$ and $z=h'$ by the basement rock. This gives the maximum possible value of the anomaly δg_z viz.,

$$(\delta g_z)_{\max} = 2\pi\rho G(h' - h). \qquad (2)$$

If $(\delta g_z)_{obs}$ is the maximum anomaly actually observed, we may be sure that

$$h' - h \geqq \frac{(\delta g_z)_{obs}}{2\pi\rho G}. \qquad (2a)$$

B. FIRST HORIZONTAL DERIVATIVE OF THE VERTICAL GRAVITATIONAL ANOMALY

By differentiating (1) under the integral sign we have

$$\frac{\partial}{\partial\xi}\Delta(\delta g_z) = 3\sigma \iint \frac{z(x - \xi)dxdy}{[z^2 + (x - \xi)^2 + (y - \eta)^2]^{5/2}}, \qquad (3)$$

where $\sigma = G\rho\Delta z$. If we put $x' = x - \xi$, $y' = y - \eta$, the contribution of the layer at depth z becomes

$$\frac{\partial}{\partial \xi}\Delta(\delta g_z) = 3\sigma \iint \frac{z x' dx' dy'}{[z^2 + x'^2 + y'^2]^{5/2}}.$$

To find, say, the greatest positive value which the layer can contribute, we include all elements for which the integrand is positive. Thus if x' is positive, we can fill up the whole of the positive half plane for any depth z. This leads to a step-like structure with its edge at $x' = 0$, extending to $\pm\ \infty$ in the y direction and of height $h'—h$. Integrating over the above range of variables, we find for the maximum first horizontal derivative of the vertical gravitational anomaly the value

$$S = 2\rho G \log h'/h. \tag{4}$$

This value applies to points along the y' axis immediately above the edge of the step. In this case, therefore, the optimum structure reduces to a two-dimensional one. If $|S_{\text{obs}}|$ is the greatest observed absolute value of the first horizontal derivative, we arrive at the limit

$$\log \frac{h'}{h} \geqq \frac{|S_{\text{obs}}|}{2\rho G}. \tag{4a}$$

C. SECOND HORIZONTAL DERIVATIVE OF THE VERTICAL GRAVITATIONAL ANOMALY

Differentiating (3) with respect to ξ, we get

$$\frac{\partial^2}{\partial \xi^2}\Delta(\delta g_z) = 3\sigma z \iint \frac{4(x-\xi)^2 - (y-\eta)^2 - z^2}{[(x-\xi)^2 + (y-\eta)^2 + z^2)^{7/2}}\, dx dy$$

$$= 3\sigma z \iint \frac{4x'^2 - (y'^2 + z^2)}{[x'^2 + y'^2 + z^2]^{7/2}}\, dx' dy'. \tag{5}$$

The sign of the integrand is that of $4x'^2 - (y'^2 + z^2)$, and the regions of positive and negative contributions are separated by the hyperbola $4x'^2 - y'^2 - z^2 = 0$, or $y'^2 = 4x'^2 - z^2$, with asymptotes $y' = \pm 2x'$ (Fig. 2). For a given z the elements in the shaded zone will provide a negative contribution. We integrate (5) first with respect to x' between limits $x' = 0$ and $x' = \frac{1}{2}(z^2 + y'^2)^{1/2}$ and then with respect to y' from 0 to ∞. This gives the negative contribution of one shaded quadrant, and therefore $\frac{1}{4}$ of the total effect of the layer thus bounded. We find

$$-\frac{1}{4}\frac{\partial^2}{\partial\xi^2}\Delta(\delta g_z) = 3\sigma z\int_0^{\infty} dy'\int_0^{\frac{1}{2}(z^2+y'^2)^{1/2}} \frac{y'^2+z^2-4x'^2}{[x'^2+y'^2+z^2]^{7/2}}\,dx'$$

$$= \frac{12\pi\sigma}{25\sqrt{5}}\,\frac{1}{z^2}.$$

Finally, integrating over z between the limits h to h', we derive for the maximum absolute value of the second horizontal derivative,

$$T = \frac{48\pi\rho G}{25\sqrt{5}}\left(\frac{1}{h}-\frac{1}{h'}\right) = 2.7\rho G\left(\frac{1}{h}-\frac{1}{h'}\right). \tag{6}$$

Both positive and negative values of any derivative have of course the

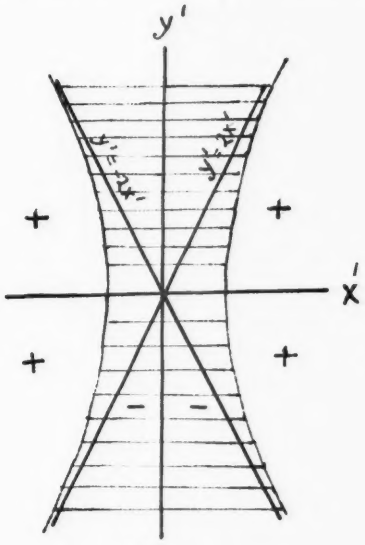

FIG. 2

same absolute numerical value, since the effect of a completely filled up layer is zero at any surface point. If now $|T_{obs}|$ is the greatest absolute value observed for the second horizontal derivative, we can say that

$$\frac{1}{h}-\frac{1}{h'} \geqq \frac{|T_{obs}|}{2.7\rho G}, \quad \text{i.e.,} \quad \frac{1}{h} > \frac{|T_{obs}|}{2.7\rho G}. \tag{6a}$$

This result is useful because it leads to an upper limit to h, the shallowest depth of the structure, viz.,

$$h < 2.7\rho G/\left| T_{\text{obs}} \right|. \tag{7}$$

It is of interest to compare this result with that which would apply to an infinitely long ridge with straight sides, since such a structure would be a more likely approximation to those geological formations which may be met with in practice. Treating this problem as a two-dimensional one, but adopting the same method as described above, we find that the maximum effect is produced by a truncated ridge, the sides of which are planes with their line of intersection on the surface and inclined 60° to the horizontal. The numerical factor in this case turns out to be 2.598 as compared with 2.7 in the case of the three-dimensional structure calculated above.

D. HORIZONTAL DIRECTING TENDENCY (DIFFERENTIAL CURVATURE) RECORDED BY THE EÖTVÖS TORSION BALANCE

Apart from the horizontal gradient, the limiting value of which has been calculated under B, the Torsion Balance provides values of the H.D.T., which is the product of 'g' and the difference between the principal curvatures of the equipotential surface passing through the point of measurement. If ξ, η denote axes directed along those of principal curvature at the observation point P, we define the H.D.T. by

$$-\left(\frac{\partial^2 U}{\partial \eta^2} - \frac{\partial^2 U}{\partial \xi^2}\right),$$

where U denotes the gravitational potential. The quantity

$$\frac{\partial^2 U}{\partial \eta \partial \xi}$$

vanishes in this case.

Our problem, therefore, is to calculate the greatest absolute value of

$$-\left(\frac{\partial^2 U}{\partial \eta^2} - \frac{\partial^2 U}{\partial \xi^2}\right).$$

Introducing as before $x' = x - \xi$, $y' = y - \eta$ we find that a layer at depth z contributes an amount

$$3\sigma \iint \frac{x'^2 - y'^2}{[x'^2 + y'^2 + z^2]^{5/2}}\, dx'dy'.$$

The integrand is positive over the shaded area bounded by $y' = \pm x'$ (Fig. 3). Integrating over this whole region gives

$$12\sigma \int_0^\infty dx' \int_0^{x'} \frac{x'^2 - y'^2}{[x'^2 + y'^2 + z^2]^{5/2}} dy'$$

$$= 8\sigma \int_0^\infty \frac{x'^3 dx'}{(x'^2 + z^2)(2x'^2 + z^2)^{1/2}} = \frac{4\rho G \Delta z}{z}.$$

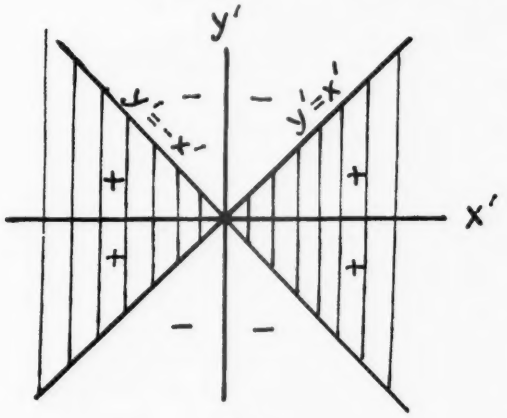

FIG. 3

A final integration over z between the limits h, h' gives for the maximum absolute value of the H.D.T. the value

$$\text{H.D.T.}_{\max} = 4\rho G \log h'/h. \tag{8}$$

It is interesting to note that a similar calculation in the case of a two-dimensional structure shows a maximum absolute value of half the above amount i.e., $2\rho G \log h'/h$. This two-dimensional structure is in the form of a long truncated ridge with sides sloping at 45°, and intersecting in the surface, the top and bottom surfaces being at depths h and h' respectively below the surface.

It would of course be possible to calculate limits for the third and higher horizontal derivatives of δg_z and so obtain upper limits for h^2, h^3 etc., from the observed maxima of these higher derivatives. In practice, however, it would not be feasible to obtain from gravity traverses sufficiently accurate values of derivatives higher than the second. Using the same method we proceed to calculate the limiting values of the vertical magnetic anomaly and its horizontal derivatives.

E. VERTICAL MAGNETIC ANOMALY

Let k denote the relative susceptibility of the basement magnetic rock, supposed magnetized inductively by the earth's field H. Let H_z denote the vertical component of H and H_x the horizontal component, supposed directed along the x axis. If $\Delta\omega$ represents an element of solid angle subtended at a surface point $P(\xi, \eta, 0)$ by an element of rock in the horizontal layer of vertical thickness Δz at a depth z, the contribution of this element to the vertical anomaly at P will be

$$k\left(H_x\frac{\partial}{\partial x}\Delta\omega + H_z\frac{\partial}{\partial z}\Delta\omega\right)\Delta z.$$

Writing

$$\Delta\omega = z\,dx\,dy\,/\,[z^2 + (x-\xi)^2 + (y-\eta)^2]^{3/2}$$

and integrating over the whole horizontal layer at depth z, we get for its contribution:—

$$kH_z\Delta z\iint\frac{2z^2 - x'^2 - y'^2 + 3\alpha z x'}{(z^2 + x'^2 + y'^2)^{5/2}}\,dx'dy'$$

with $\alpha = H_x/H_z$ and $y' = y-\eta$, $x' = x-\xi$ as before. The boundary between positive and negative contributions will be the circle $x'^2+y'^2-3\alpha z x'-2z^2=0$, and the greatest positive effect of the layer will therefore be found by integrating over the interior of this circle, at all points of which the integrand is positive. Had we considered the vertical component only of the earth's field, the section of optimum structure would have been a circle of radius $z\sqrt{2}$ with its center vertically beneath the point of maximum vertical anomaly. The optimum structure would then be a truncated cone with apex at the surface point. This case, which admits of immediate integration over x', y' and z, leads to a maximum anomaly of

$$\frac{4\pi kH_z}{3\sqrt{3}}\log h'/h = 2.42kH_z\log h'/h.$$

The effect of the horizontal component of the earth's field is to displace the center of the circular cross-section in the positive x direction through a distance $\frac{3\alpha z}{2}$ and to increase its radius to $z\sqrt{2+\left(\frac{3\alpha}{2}\right)^2}$.

The integration over x', y' is best performed graphically after transforming to polar co-ordinates $x' = r\cos\phi$, $y' = r\sin\phi$. This allows im-

mediate integration over r for a fixed ϕ. The lower limits of the r integrals in this case are zero and the upper limits are found graphically for different values of ϕ. The area of the curve obtained by plotting ϕ and the definite integral gives the total required effect of the horizontal layer. If we take $\alpha = H_x/H_z = 0.42$, the layer at depth z contributes $2.57\ kH_z/z$ and so the maximum vertical anomaly for a range of z between h and h' would be

$$(\delta H_z)_{\max} = 2.57 kH_z \log h'/h. \tag{9}$$

As in the case of the first horizontal derivative of the gravitational anomaly, this can be used to provide an upper limit to the ratio h'/h.

F. FIRST HORIZONTAL DERIVATIVE OF THE VERTICAL MAGNETIC ANOMALY PERPENDICULAR TO MAGNETIC MERIDIAN (MERIDIAN PARALLEL TO x OR TO ξ AXIS)

We find

$$\frac{\partial}{\partial \eta}\left(\frac{\delta H_z}{kH_z}\right) = \int_h^{h'} dz \iint \frac{3y'(4z^2 - x'^2 - y'^2 + 5\alpha z x')}{(z^2 + x'^2 + y'^2)^{7/2}}\, dx'dy'.$$

Thus, for a positive value of the derivative, we require the sign of $4z^2 - x'^2 - y'^2 + 5\alpha z x'$ to be the same as that of y'. The numerator of the integrand is, as in the previous cases, homogeneous in powers of x', y', z, and the final integral over z will be of the form

$$A \int_h^{h'} \frac{dz}{z^2} = A\left(\frac{1}{h} - \frac{1}{h'}\right),$$

where A is the numerical value of the double integral in the $x'y'$ plane when z has the value 1. The center of the boundary circle $x'^2 + y'^2 - 5\alpha x' - 4 = 0$ in the plane at unit depth ($z = 1$) is displaced by a distance 1.05 in the x' direction, if α is given the value 0.42 (Fig. 4). The region of integration is the interior of the semicircle for positive y', and for negative y' it will be over the external region to infinity. The contribution to A of the interior of the semicircle is found graphically to be 2.35. The effect of the complete half plane for y' positive is found by immediate integration to be 2. Thus the positive y' region outside the semicircle must contribute -0.35. The contribution of the corresponding region for y' negative will therefore be $+0.35$, and the total value of A for the shaded area is accordingly $2.35 + 0.35 = 2.70$. The maximum value of the first horizontal derivative perpendicular to the magnetic meridian will therefore be $2.7\ kH_z(1/h - 1/h')$.

As in the case of the second horizontal derivative of the gravitational anomaly, this gives an upper limit to h.

PARALLEL TO MAGNETIC MERIDIAN

For $\partial/\partial\xi(\delta H_z/kH_z)$ positive, the cross-section for unit depth ($z=1$) has the form shown in Fig. 5, the shaded regions being occupied by magnetic matter. The equation to the boundary between positive and

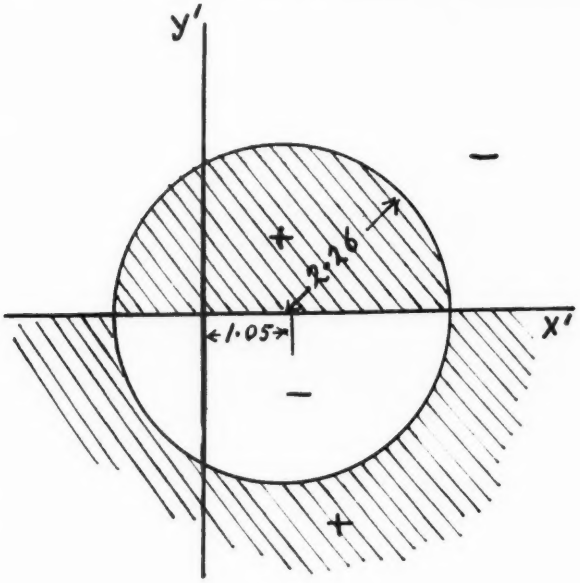

FIG. 4

negative regions is now $3x'[4-(x'^2+y'^2)]-3\alpha[1+y'^2-4x'^2]=0$. On carrying out the integrations graphically, the extreme value is found to be the same as in the former case viz., $2.70\ kH_z(1/h-1/h')$.

To summarize, if the magnetic meridian is along the x axis and the ratio of horizontal to vertical component of the earth's field is 0.42, then

$$\left[\frac{\partial}{\partial\xi}(\delta H_z)\right]_{\max}=\left[\frac{\partial}{\partial\eta}(\delta H_z)\right]_{\max}=2\cdot7\ kH_z\left(\frac{1}{h}-\frac{1}{h'}\right). \qquad (10)$$

This value may be compared with the value which would be found for the vertical part of the earth's field acting alone. By immediate integration this is found to be $2.58\ kH_z(1/h-1/h')$.

G. SECOND HORIZONTAL DERIVATIVE OF THE VERTICAL MAGNETIC ANOMALY

The limiting value of $\partial^2/\partial\xi^2(\delta H_z)$ either parallel or perpendicular to the magnetic meridian could be found by the same general method, but in order to avoid very laborious calculations, the value is calculated in this case taking account of the vertical component of the

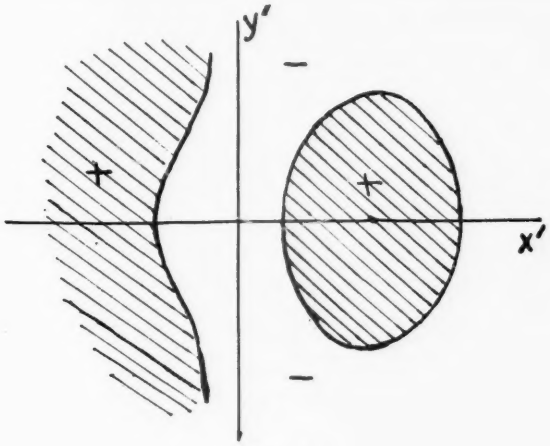

FIG. 5

earth's field only. Inclusion of the horizontal component should increase this value somewhat, just as it does in the case of the anomaly itself and its first derivative.

Under these conditions ($\alpha=0$), we have

$$-\frac{\partial^2}{\partial\xi^2}(\delta H_z)$$

$$=3kH_z\int_h^{h'}dz\iint\frac{4z^4-27z^2x'^2+3z^2y'^2+3x'^2y'^2+4x'^4-y'^4}{[x'^2+y'^2+z^2]^{9/2}}\,dx'dy'.$$

For regions where the numerator of the integrand is positive, we have contributions to the negative value of the second derivative. This leads to a complicated type of cross-section of the form shown in Fig. 6, taking z unity.

The shaded areas indicate those portions of the horizontal cross-section at unit depth which contribute to the negative second derivative at a surface point immediately over the origin. The double integral

over the central shaded area has the numerical value 5.81, and that over the outer shaded area has the value 0.176. Thus the effect of the central part of the structure is about 30 times that of the outer part.

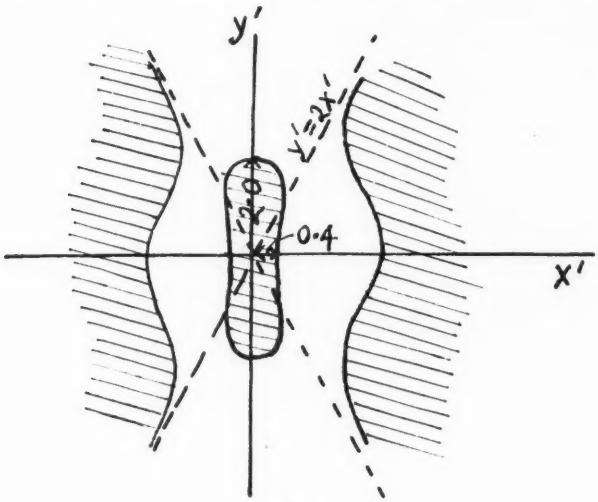

FIG. 6

A layer of thickness Δz at a depth z will therefore contribute an amount $5.99\, kH_z(\Delta z/z^3)$ to the negative second derivative. Integrating over z we have

$$\left[-\frac{\partial^2}{\partial \xi^2}(\delta H_z)\right]_{\max} = 3kH_z\left(\frac{1}{h^2} - \frac{1}{h'^2}\right), \tag{11}$$

or, if T denotes the maximum observed absolute value of the second derivative, $h<\sqrt{3kH_z/T}$, and this may provide a useful indication of an upper limit for the shallowest depth of the structure. The same numerical factor applies to the positive values of the second derivative, so that only the absolute values need be taken into account.

ACKNOWLEDGMENTS

I wish to thank Dr. J. H. Jones of the Anglo-Iranian Oil Company for his kind help in checking some of the numerical computations, and also to express my thanks to the Chairman, Lord Cadman, and Directors of the Company for permission to publish these results.

THE GULF GRAVIMETER*

R. D. WYCKOFF†

ABSTRACT

The design features of the Gulf gravimeter[1] are presented accompanied by a brief discussion of general gravimeter design problems. In addition to the description of the unastatized instrument which is the type finally selected for commercial development, brief consideration is given to two astatized instruments including a bifilar gravimeter the construction of which was carried to completion.

INTRODUCTION

Gravimetric surveying has, until recent years, suffered from a lack of adequate instrumentation properly to adapt it to the role for which it is best fitted. To alleviate this situation arising from the fact that the torsion balance is inherently a detailing device, ill adapted to reconnaissance, consideration was given to direct gravity measurements whereby the limitations of the gradient method could be eliminated. This led to the early development of the pendulum method and while commercial use of the apparatus has been rather limited in the industry at large, a considerable amount of such work was done within the Gulf Oil Corporation organization. However, while this work demonstrated that creditable performance may be achieved with properly designed pendulum equipment, it was recognized at the start that greater speed and the attendant decrease in cost would be necessary if gravity surveying was to maintain its deserved scope of operation. Acknowledging this fact and recognizing that inherent limitations in the pendulum method precluded attainment of this end, early in November 1932 Dr. Eckhardt instigated investigation of the gravimeter design problem at the Gulf laboratory. Early in 1933 definite plans had been outlined and laboratory work was well underway.

With the view to minimize delay in providing a field-worthy instrument the plan involved the simultaneous investigation and construction of two distinctly different models well known at the time and now commonly referred to as the astatized and unastatized types. By following this procedure the necessity of making a final choice as

* Presented at the Annual Meeting, Chicago, April 9, 1940.

† Gulf Research & Development Co., Pittsburgh, Pa.

[1] A. Hoyt, U. S. Patent No. 2, 131,737, issued 10/4/38, appl. 8/5/35.

to type was postponed until a rational selection could be based upon actual experience with each type. At the end of 1934, after two years' elapsed time, an unequivocal selection was possible and in March 1935 a successful field trial of one of the instruments was made in the coastal area of Texas. This instrument, supplemented by improvements where experience indicated the need, represents the gravimeter which has been used by the Gulf organization since the first eight were put into operation and completely supplanted the pendulum equipment in 1936.

It is the purpose of this discussion to present the results of the above investigation. Attention will be confined primarily to a specific instrument but in so doing it will be necessary to consider briefly the instrumental requirements and the salient features of the two types mentioned above. No attempt will be made to provide a comprehensive discussion of gravimeter design problems and an exhaustive comparison of the various instruments now in use would be quite unjustified.

GENERAL CONSIDERATIONS IN GRAVIMETER DESIGN

SENSITIVITY REQUIREMENTS

Experience amply demonstrates that even for reconnaissance prospecting purposes, a satisfactory gravimetric survey requires an instrument having a probable error not exceeding 0.1 milligals and preferably less. The lowest limit to be assigned is for obvious reasons determined by practical considerations involving the accuracy with which elevation and topographic corrections[2] can be made and by erratic surface and near-surface influences arising from density variations. While the magnitude of these spurious and uncontrollable effects will vary depending upon the geological and terrain environment, it is probably safe to say that little practical significance can be attached to the attainment of an accuracy exceeding 0.05 mg. unless such accuracy is available without sacrifice of operational convenience. Except for very special applications the utilitarian advantage of an instrument of such precision lies in the assurance that the normal observational errors will be below the "noise level" due to terrain and topographic uncertainties, and that from normal probability considerations, the number of stations exceeding 0.1 mg. error will be correspondingly reduced.

[2] Elevation corrections:—free air correction = 0.094 mg./ft. or including Bouguer correction = 0.07 mg./ft. approx.

Accepting for the purpose of discussion that a probable error not exceeding 0.1 mg. is desired, and recalling that in the gravimeter-type instrument the total force of gravity, 980,000 mg., is operating, the minimum sensitivity required is approximately 10^{-7} g. Since this requirement of measuring a force to better than one part in 10,000,000 must be accomplished by a portable instrument easily manipulated in the field under any adverse terrain and weather conditions encountered, and must be sufficiently rugged to withstand reasonably rough handling and transportation, some of the difficulties in design will be evident. In fact *absolute* measurements of any force with that accuracy have not and are not likely soon to be attained.

The gravimeter is retrieved from this apparently hopeless situation by the use of proper operating methods since unpredictable instrumental drift is readily determined by the simple expedient of returning at suitable time intervals to reobserve a previously occupied station. If the "drift curves" obtained in this manner are relatively smooth and contain no sudden breaks, reliable observations may be possible even though random long-period fluctuations or drift may be several orders of magnitude greater than the probable error specified. Evidently then the term gravimeter is somewhat of a misnomer. A strictly applicable term would be *gravity comparator* for this designation eliminates the implication of long-term stability usually associated with indicating instruments and its use might eradicate the skepticism of the uninitiated when a geophysicist speaks glibly of the accuracy of gravity measurements in terms of parts in one hundred million. Here we will at least qualify the term gravimeter with the understanding that the instrument is a comparator.

UNASTATIZED TYPE (LINEAR SYSTEM)

In our original investigations starting in 1933 all efforts were soon concentrated upon instruments of the type involving a constant mass the weight of which is balanced by a comparison force derived from a suitable spring. In its simplest form such a balance comprises merely a mass supported by a helical spring in conjunction with a device to indicate the equilibrium position of the mass.

It is evident that if in an elemental device of the above type (Fig. 1a), S is the total displacement of the spring-mass system under the action of total gravity g, then the sensitivity of the device as a gravimeter will be:

$$\Delta S = S \cdot \Delta g/g. \qquad (1)$$

That is, a change in the gravitational force of 10^{-7} g is accompanied by a change in the position of the weight amounting to 10^{-7} times the total initial displacement. Hence, if we assume 20 cm. (5 inches) as the maximum displacement of a spring which can be incorporated conveniently in a portable instrument we obtain a displacement:

$$\Delta S = 2 \times 10^{-6} \text{ cm.} \quad \text{when} \quad \Delta g = 10^{-7}\, g.$$

This displacement amounts to about 1/30 of the fringe separation in an interferometer or about 100 times smaller than the limiting resolution of a precision micrometer microscope. Since we have been speaking of minimum sensitivity requirements it is evident that without some amplification of the motion of the suspended mass, neither the microscope nor interferometer is applicable. In fact, for other reasons we may eliminate the latter device from any further consideration.

Adopting the micrometer microscope as a suitable measuring device because of its convenience, we may assume that a displacement of 0.001″ or 2.5×10^{-3} cm. is directly observable with ease. But we have seen that in a portable gravimeter of the elemental spring-balance type a displacement of 2×10^{-6} cm. must be detected with certainty, so it is evident that an amplification of at least $\times 1000$ must be incorporated between the mass system and the observed index point. While a portion of this amplification may be obtained by optical means, full advantage of optical levers can be secured only when a rotational motion is available. This is a disconcerting situation which is met in some instruments by mechanical conversion systems which amplify directly by levers or convert the linear motion of the suspended mass into a rotational motion of small mirrors. Since any auxiliary attachments of this kind introduce hinge or pivot points and ligaments contributing extraneous restoring forces, and necessarily introduce multiple constraint in the moving system, tending to aggravate level sensitivity, a strenuous effort was made to retain the simplicity of the simple spring balance. The problem was finally solved in the Gulf instrument by incorporating the rotational feature within the spring itself as will be explained later.

ASTATIZED TYPE (NON-LINEAR SYSTEM)

Thus far we have mentioned only the method of applying amplification between the moving mass and the reading device and noted that for adequate sensitivity an amplification $\times 1000$ or greater must be obtained.

An alternative method involves increasing the actual motion of the moving mass by the method commonly called astatization. If it were possible to introduce an absolutely constant restoring force to balance say 99% of the total weight of the moving system then the apparent sensitivity of the balance operating as a gravimeter could

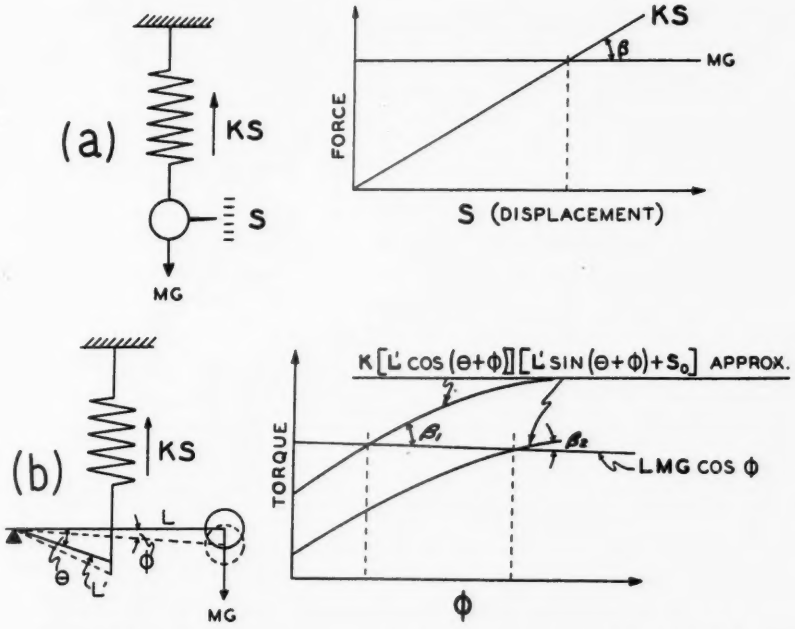

FIG. 1. Schematic diagram of unastatized (a) and astatized (b) spring balances. K=spring constant. The schematic force/displacement curves (b) illustrate the principle of astatization.

be increased 100 fold. While this ideal astatization of a spring-balance system has never been attained, it has been simulated by innumerable well known methods exemplified by the Galitzin vertical seismograph and its numerous modifications or the bifilar gravimeter.[3]

Fig. 1 shows schematically a comparison of the unastatized spring balance and a typical astatized system though it should be emphasized that these figures are intended merely to indicate the essential difference in the mechanics of the two types.

[3] That is, Tomaschek and Schaffernicht, "The Temporal Variation in the Force of Gravity," Annalen d. Physik, Vol. 15, p. 787, (1932).

In the case of the elemental balance of Fig. 1a, the forces acting are obviously the constant weight Mg supported by the opposing spring tension which increases linearly with displacement at a rate proportional to the spring constant K. As indicated by the Figure the equilibrium displacement is shown by the intersection of the curves KS and Mg. It is also evident from the Figure that the sensitivity of the device as a gravimeter will increase as angle β decreases; a result which, because of the linearity of curve KS, can be accomplished only by increasing the equilibrium elongation of the spring. Obviously this is merely a restatement of Eq. 1 but is intended to emphasize the fact that in any spring balance system having a strictly linear restoring-force curve, KS, the initial or equilibrium displacement uniquely determines its gravimetric sensitivity.[4]

On the other hand, while the ideally astatized system would be linear, practically attainable systems are of the non-linear type indicated in Fig. 1b, the turning moment or torque functions being dependent upon the geometry of the system. Thus, by attachment of the spring to the lever L' rather than on the center line L between the mass and knife-edge, the instrument represented by Fig. 1b may be adjusted so that its equilibrium point is anywhere along the restoring-torque curve:

$$T = K[L' \cos(\theta + \phi)][L' \sin(\theta + \phi) + S_0]. \text{ (approx.)} \qquad (2)$$

Thus angle β may be made arbitrarily small and the sensitivity arbitrarily great, up to the point of instability when $\beta = 0$. Hence by devices equivalent to Fig. 1b it is possible to simulate the behavior of extremely long springs and thereby attain very high sensitivities. However, it is evident that with each change in adjustment, the sensitivity and hence the scale value of such an instrument will be changed. Moreover, even for a fixed adjustment, the non-linear feature precludes a strictly linear scale, although over a limited range which may be extended by the use of further geometrical complexity and auxiliary spring arrangements, reasonable linearity may be achieved. This inherent non-linearity of the so-called astatized devices is inconvenient and while certain design features may alleviate this handicap, it con-

[4] Evidently the actual physical elongation of a spring may be made somewhat less than the effective elongation by the expedient of pre-stressing the spring when forming it. However, this merely suppresses its zero and in speaking of its displacement we refer to effective elongation.

stitutes the principal objection to this type. Moreover, it practically dictates the design of a null rather than a deflection type instrument.

It is of interest to note that the gravimetric sensitivity of any spring balance is determinable from the period of the system, and this provides a direct and simple criterion whereby a comparison of various types may be made. Thus in any simple harmonic system such as a weight in equilibrium with a linear restoring force the period, T, in seconds is given by

$$T = 2\pi(M/Kg)^{1/2}, \tag{3}$$

where:

M = Mass in gms.

K = Spring constant in gms/cm.

g = Acceleration of gravity in dynes.

But $M/K = S_0$, the initial or equilibrium displacement of the spring, therefore

$$T = 2\pi(S_0/g)^{1/2}, \tag{4}$$

$$T^2 = (4\pi^2/g)S_0. \tag{5}$$

Hence from Equations 1 and 5, we may say that the gravimetric sensitivity of any spring balance is proportional to the square of its period and moreover this applies not only to the linear but to the astatized systems[5] which cannot be compared on the basis of any other simple criterion.

Consider for example a simple spring balance, Fig. 1a, having a total spring displacement of 20 cm. and a sensitivity, mentioned earlier, of 2×10^{-6} cm. per $10^{-7}g$. The period of the system is (Eq. 4) approximately 0.9 seconds. Now in order to obtain an increase in sensitivity of 100 fold, the device of Fig. 1b may be adjusted to a period of 9 seconds. With such an adjustment the instrument simulates the performance of an elemental balance having an equilibrium displacement of more than 2000 cm. and yet in the astatized system the actual elongation of the spring need not exceed a few centimeters.

[5] This is true, of course, only to the extent that we may neglect inertial components in the system other than those upon which gravitational force is acting. For example, the rotational moments of the beam system of Fig. 1b represent extraneous inertial factors which increase the period of the system without affecting the gravimetric sensitivity. Obviously the period may be corrected for these spurious effects before computing the sensitivity.

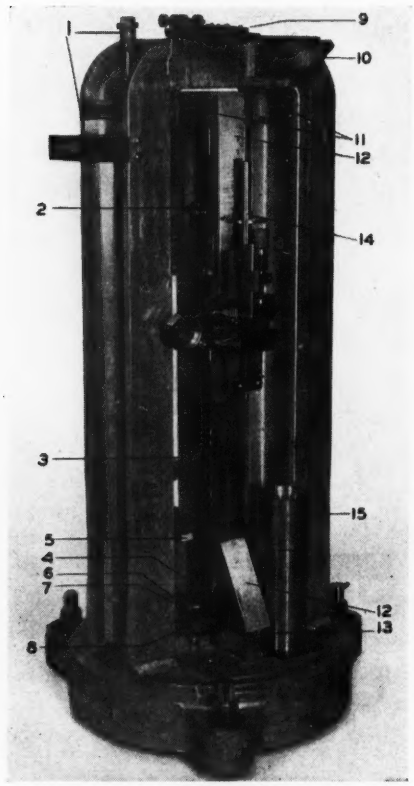

FIG. 2. Galitzin Type Gravimeter.

1. Knife-edge lift and clamp control
2. Main-spring tension adjuster
3. Main-spring
4. Mass
5. Fixed mirror for multi-reflection
6. Moving mirror (top of knife-edge)
7. Knife edge
8. Lifter and clamp arm
9. Entrance optical slit and exit window to photo recorder
10. Optical system for level (15)
11. Micro-adjustment of spring angle
12. Main spring support
13. Main spring support hinge
14. Auxiliary-spring micrometer control
15. Pendulum type level

This method of effectively amplifying the displacement of the moving mass, together with the use of a very moderate optical amplification, results in a compact device of high sensitivity and presents a most alluring picture the disadvantages of which, along with the advantages, can only be fully appreciated through experience.

GRAVIMETER CONSTRUCTION

ASTATIZED TYPE

Mention was made that our plan of investigation involved construction of both astatized and unastatized types. In view of existing information regarding the former type and the immediate need for an instrument of high sensitivity in which to test the performance of various springs and spring materials, an experimental model was constructed which was nothing more than a modified Galitzin vertical seismograph with a knife-edge support in place of the usual hinge. It was adapted to continuous photographic recording to facilitate examination of the performance characteristics of the springs. The design is that shown schematically in Fig. 1b with necessary refinements to permit micro-adjustments of spring tension and alignment angle of the spring with respect to the axis of the moving system. The experimental instrument is shown in the photograph, Fig. 2.

With a properly thermostated container which maintained the temperature constant to 0.001°C. this instrument easily could be adjusted to a period of 10 or 12 seconds and periods in excess of 25 seconds were maintained for 24 hours or more. In Fig. 3 the circled points represent deflections as read from a photographic record after subtracting a linear drift and indicate the excellent performance obtained when the period was adjusted to approximately 22 seconds. These data are presented merely to show the extremely high sensitivity obtainable through the use of the astatization principle.

While this instrument was provided with an arresting and clamping device, for various and rather obvious reasons no serious attempt was made to adapt it to field use. It served admirably, however, as a spring tester and incidentally to develop tangible experience and familiarity with the problems involved in instruments intended to operate at sensitivities in excess of $10^{-7}g$.

Fig. 4 shows the important features of a bifilar gravimeter designed as a portable instrument and having adequate sensitivity for gravimetric surveys. It represents our attempt to build a field-worthy instrument incorporating the astatization principles. While this bifilar

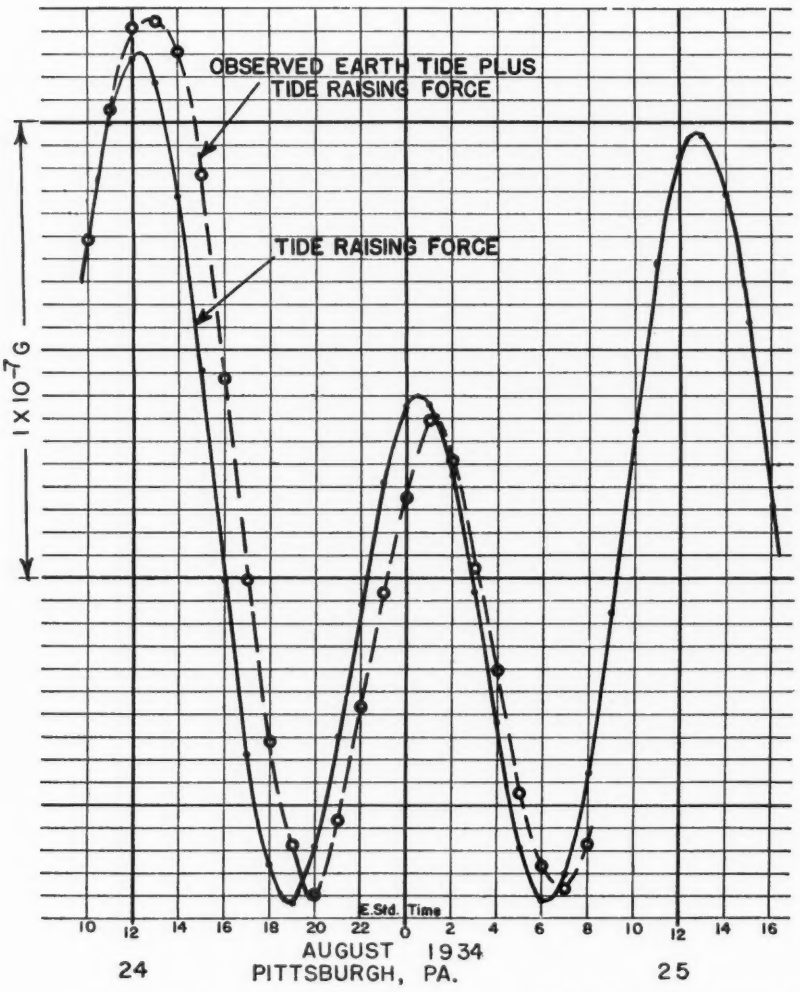
OBSERVED EARTH TIDE PLUS TIDE RAISING FORCE
TIDE RAISING FORCE
1 X 10⁻⁷ G
E.Std. Time
10 12 14 16 18 20 22 0 2 4 6 8 10 12 14 16
AUGUST 1934
24 PITTSBURGH, PA. 25

FIG. 3. Gravity variations due to tidal forces and associated phenomena presented to show the high sensitivity obtainable with compact instruments of the astatized type.

design and construction was carried through to completion it was never given a field test although laboratory operation indicates reasonably satisfactory performance and ruggedness. Of special interest is the calibrating weight and the auxiliary sylphon-bellows arrangement to provide pressure variations for the buoyancy method of calibration. These self-contained calibrating devices were provided in order con-

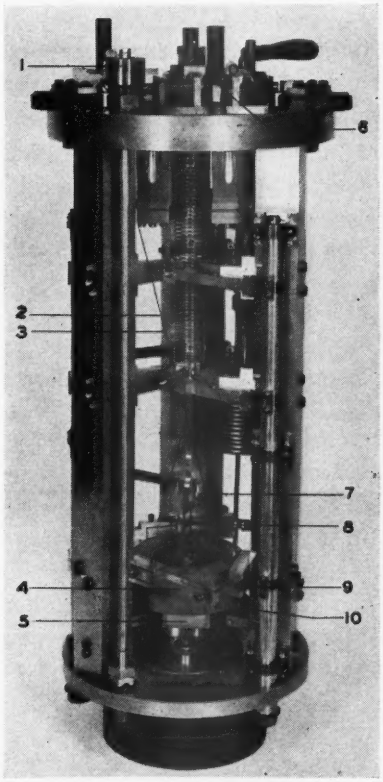

FIG. 4. Bifilar Gravimeter.

1. Clamp control
2. Spring-tension supports most of mass, torsion opposes bifilar torque
3. Bifilar suspension—Drawn in to make visible
4. Clamp arm
5. Mirror on moving system
6. Torsion head adjuster
7. Calibrating weight
8. Mass
9. Ligament operating clamp-arm
10. Damping magnet

veniently to determine the scale value of the instrument for any desired adjustment and to detect the drift in sensitivity which might easily occur in a device of this type. It appeared to be the logical method of combating the inconvenient non-linear characteristics of this type of instrument.

UNASTATIZED TYPE

We have already discussed the sensitivity requirements of an elemental spring balance and concluded that a magnification of approximately ×1000 would be required between the moving mass and the

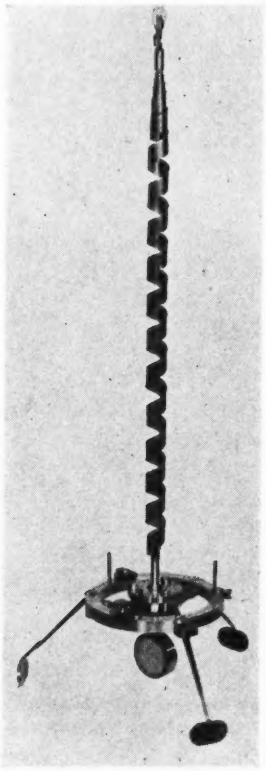

FIG. 5. Complete moving system of Gulf Gravimeter.

observed index point. The desirability of eliminating any lever systems or other mechanical amplifying schemes will also be apparent.

Fig. 5 shows the spring-mass system of the Gulf gravimeter and it will be noted that it retains the extreme simplicity and desirable features of the elemental spring balance of Fig. 1a—a helical spring supporting a moving mass with no ligaments, levers, or other attachments. The unique feature is, of course, the use of a ribbon helix which, in the spring illustrated, produces a rotation of about 1 second

of arc per 10^{-7} change in g. This is equivalent to an initial deflection under total g of approximately 2880° or 8 revolutions. The rotation of the suspended mass is observed by means of an attached mirror which in conjunction with a special multiple-reflection mirror arrangement permits reading the straight-through, or undeflected beam together with multiple reflections readable beyond the 6th. Using the 4th reflection and an optical lever 22″ in length, 0.1 milligal corresponds to a 0.001″ displacement of the index under the micrometer-microscope. Experience indicates that the instrument can be read to about ten times this accuracy although, of course, the usable sensitivity is somewhat less.

Certain very important operating advantages are available with the simple moving system of Fig. 5, for in addition to adequate sensitivity when used in conjunction with moderate optical amplification, the adjustment of the instrument has no marked effect on the scale value or calibration constant. The total range of the micrometer reading device is 25 to 30 mg. depending upon the particular spring involved but it is a very simple matter to adjust the instrument for operation in any area regardless of the magnitude of g, and the calibration constant is unaffected by such adjustments. The moving system is suspended from a torsion head provided with micrometer adjustment which is available to the operator at any time by merely inserting a special adjusting shaft through an opening in the top control panel. Thus, if in the course of a day's work gravity variations exceed the range of the scale the operator merely shifts the zero of the instrument by means of the torsion head adjustment and proceeds without appreciable loss of time or change in calibration constant. Instruments which have been in service for several years have checked their original calibration within 0.5% and better.

Another convenient feature of the moving system arising however from the nature of the spring material rather than its design, is the fact that the rate of drift is adjustable within reasonable limits. While the principal criterion of a good spring is a *uniform* rate of creep, it is nevertheless very convenient to work with an instrument having a low rate of drift. In the Gulf gravimeter the *direction* of creep is a function of the stress in the spring and by merely adjusting the mass to the proper value so as to operate at or near the point of reversal, the creep rate may be made relatively small. A typical instrument operating in a fixed location and observed by the author for some 30 days, showed a drift of about 0.3 mg./24 hrs., although, of course, in actual

field operation the drift would depend somewhat upon operating conditions.

DAMPING

To facilitate accurate reading and rapid operation the moving system must be properly damped. This is necessary not only to eliminate natural oscillation of the system immediately after it is unclamped but to prevent the building up of sustained oscillations due to microseisms, wind, traffic, and other disturbances. In the Gulf instrument the circumstances are unusually favorable for their elimination. Ordinary short-period seismic disturbances cause vertical displacements of the weight and are not observable in the optical system since the index point is deflected by rotation and only inappreciably by translational movements of the mirror. Now the longitudinal period of the system in Fig. 5 is about 0.7 to 1 second whereas the rotational period is approximately 7 seconds. This disparity in natural period between the vertical and rotational modes, of which only the latter affects the optical system, results in a very inefficient conversion of short period seismic disturbance to scale deflection. Of course long-period earthquake and similar disturbances are observed but due to the small coupling between vertical and rotational modes at high frequencies the ordinary short-period disturbances unless of great magnitude are effectively filtered out by the moving system itself.

Electromagnetic damping is used and is obtained in the conventional manner by a metallic vane moving through the air gap of a permanent magnet. The damping vanes indicated in Fig. 5 are extended to a large radius with the view to increase both the damping and the rotational moment of inertia of the system. It is evident that damping is applied to both vertical and rotational motions of the system but most effectively to the important rotational mode.

LEVEL SENSITIVITY

One of the most disconcerting problems encountered in all gravimeters is the elimination of level sensitivity. This is particularly true of certain types which inherently are as sensitive to level as to changes in gravity. In the Gulf instrument it is evident that the absence of any mechanism attached to the moving system, that is the absence of any multiple restraint on the moving mass, eliminates the most potent sources of level sensitivity. However, in its action as a plumb-bob there is bending of the spring immediately adjacent to the support and this bending is partially converted into rotation by the ribbon

helix. By the simple expedient of tapering the helix at this point the rotational tendencies are effectively compensated. Alternatively, other supporting means which permit bending unaccompanied by rotation have been used.

We are accustomed to speak of level sensitivity in terms of level tolerance, that is the amount the instrument may be shifted off level in the direction of maximum sensitivity before the instrument deflection reaches a value of 0.1 mg. This level tolerance differs in individual instruments ranging from 10 to 12 seconds of arc in the worst case to more than 60 seconds, and is due partly to uncompensated effects

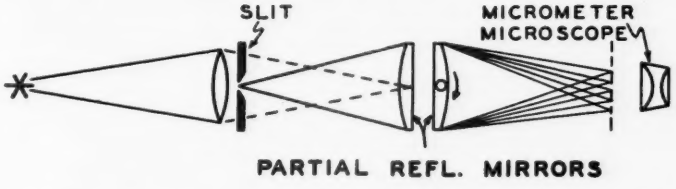

FIG. 6. Schematic diagram of multiple-reflection optical system in Gulf Gravimeter. Multiple images of slit are observed by micrometer-microscope.

incident to the above mentioned bending of the spring near the point of support but primarily to spurious effects in the damping system.

The instrument is provided with a pair of 10″ spirit levels with the usual 90° azimuthal arrangement. Since this permits leveling the instrument to an accuracy of a few seconds of arc no difficulty is encountered in normal operations in view of the instrumental level tolerance stated above. The level adjustment is accomplished by means of the conventional three-screw arrangement the only novel feature being in the construction of these screws whereby the threads as well as a ball thrust bearing operate in an oil bath and dust is permanently eliminated.

OPTICAL SYSTEM

The arrangement of the optical system is shown schematically in Fig. 6. The moving and fixed mirrors are combined with the lens system so as to eliminate unnecessary loss of light. The flat sides of the plano-convex lenses are good optical flats and are coated by an evaporation process with a partially reflecting aluminum film which, for optimum light intensity at the eyepiece, has a transmission coefficient of approximately 12%.

An important feature of the optical system is the fact that shifting

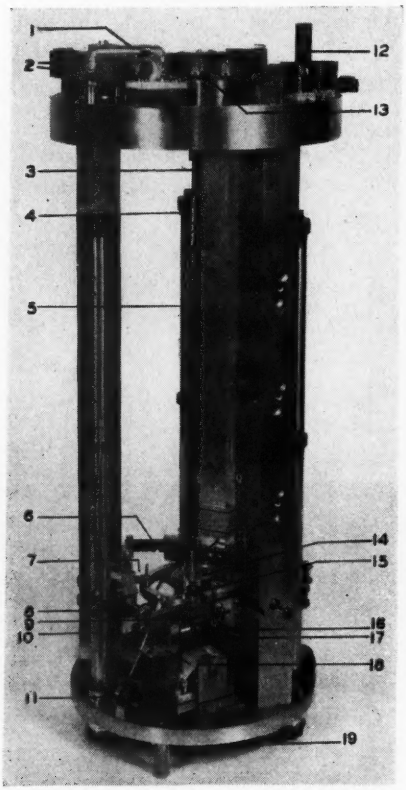

FIG. 7. Gulf Gravimeter.

1. Thermometer
2. Levels
3. Temperature compensator
4. Level-sensitivity minimizer
5. Ribbon spring
6. Clamp-arm stop
7. Clamp
8. Ligament operating clamp-arm
9. Clamp-arm
10. Clamp shaft (3)
11. Electromagnetic damping
12. Torsion-head adjuster
13. Optical slit
14. Alignment adjustment for mass
15. Mass
16. Moving mirror
17. Fixed mirror
18. Prisms
19. Clamp-control gear reduction

of the light source (slit) or the eyepiece cannot introduce errors since the zero position, or undeflected image, is always available as a reference or true-zero index. A micrometer reading from this index to any one of the multiple-reflection images provides a measure of the rotational deflection of the moving system which is free from any zero-

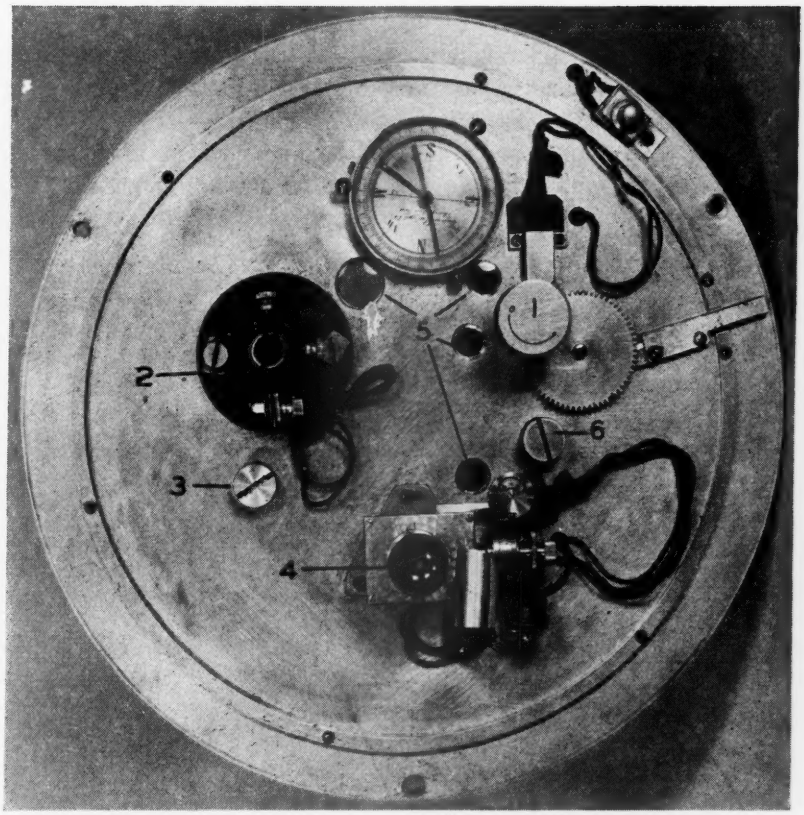

FIG. 8. Gulf Gravimeter control panel.

1. Clamp control
2. Light source for slit
3. Opening for torsion-head control
4. Micrometer-microscope
5. Level windows
6. Opening for pressure equalizing control

shift errors. Moreover, since reflections beyond the 6th order are readable and the displacement of the image is two times the order of the reflection, a reading on the 4th may be independently checked by a simultaneous reading on say the 6th reflection and thus elimination of gross reading errors is possible. The micrometer-microscope used is a conventional type reading to 0.0001″/division. The average Gulf instrument has a scale constant of 100 divisions/mg. on the 4th reflection so that no difficulty is experienced in reading to better than 0.05 mg. under routine conditions.

CLAMPING DEVICE

Fig. 7 shows the complete assembly of the instrument proper in which the arrangement of the clamping mechanism may be seen. The three V-grooved clamping lugs on the moving mass (Fig. 5) are engaged by three ball-tipped pins on the clamping arms (Fig. 7). The clamp-arms are actuated by a single control-shaft through reduction gearing which operates the three clamp-shafts and thence through

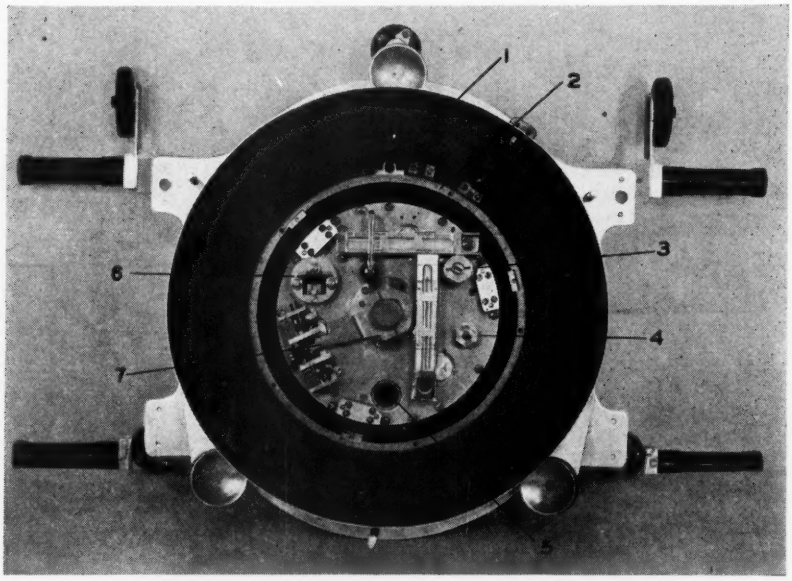

FIG. 9. Top view of Gulf Gravimeter assembly—Control panel and top insulation disc removed.

1. Thermostat well
2. Heater shell
3. Clamp control
4. Pressure equalizing valve
5. Exit window—indicator light
6. Entrance slit—indicator light
7. Torsion head adjuster

ribbon ligaments attached to the ends of the clamp-arms which pivot on hinges. Adjustments provided are adequate to permit precision adjustment of the clamps and if proper care has been taken the moving system may be clamped without seriously disturbing the images in the reading microscope.

Fig. 8 shows the top plate or operating panel of the instrument. It will be noted that the clamping control is provided with a safety de-

vice which causes a lug to project beyond the edge of the top plate when the moving system is unclamped. In this position it is impossible to place the dust cover on the instrument and if the operator has neglected to clamp the system he is warned before the instrument is moved.

TEMPERATURE CONTROL

While the material used in the spring has a low temperature coefficient and is supplemented by a temperature compensator, no attempt has been made to operate without temperature control. Fig. 9 shows a top view of the instrument with the upper insulation pad and top plate removed.

The instrument proper is suspended within a thermostatically controlled heater shell which in turn is surrounded by insulating material of low thermal conductivity protected on the outside by a thin aluminum cylinder. The heater shell is arranged to surround the instrument completely and the heater winding is distributed over the entire shell including the top and bottom of the cylinder. Temperature control is obtained by means of a conventional mercury-type thermostat mounted in a well attached to the outside of the heater can. A suitable relay operating with a few milliamperes control-current from the thermostat serves to handle the heater current supplied by a 12-volt battery. The instrument is, of course, maintained at a temperature higher than the maximum ambient temperature and the total heat dissipation of the system is about 0.4 watt/°C. temperature difference. This moderate power drain permits the use of a small battery when unusual portability is required, the total weight of such auxiliary temperature control equipment including battery is 45 lbs. as compared with 85 lbs. for normal use.

Tests have shown the control to be good to .001°C. for short periods or when not transported and 0.02°C. over long periods in field operation.

MAGNETIC SENSITIVITY

In the early Gulf instruments the moving system exhibited a slight permanent magnetic moment resulting in a spurious sensitivity to horizontal magnetic fields. In the earth's field this sensitivity was such as to require orientation of the instrument to within ± 5 or 10 degrees in a specified azimuth to be within a 0.1 mg. tolerance. Since it is a relatively simple matter to orient within less than 1 degree with an ordinary compass obviously no serious errors were introduced from

this cause. However, in more recent instruments this inconvenience has been eliminated, the magnetic sensitivity in any ordinary magnetic fields being entirely negligible.

FIELD OPERATION

In common with most gravimeters, the speed of operation is very

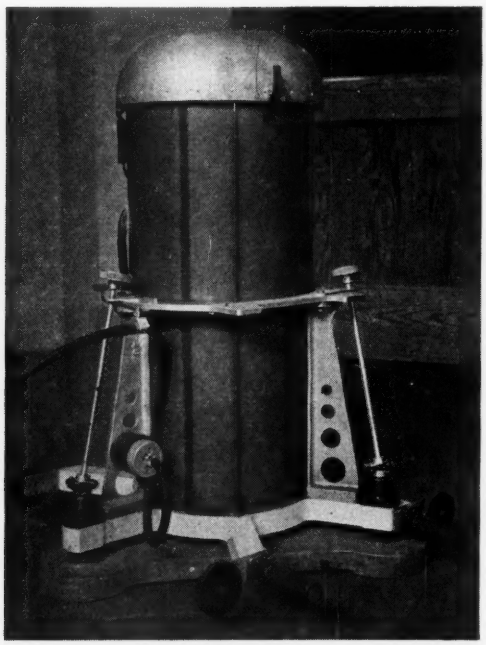

FIG. 10. Gulf Gravimeter showing yoke near center of gravity for supporting it in transportation, dust cover, leveling screws, carrying handles and temperature control cable.

Total weight of instrument proper 25 lbs.

Total weight of complete instrument 95 lbs.

Total weight of battery and control equipment 45–85 lbs.

rapid, the time involved in actually reading the instrument being negligible in comparison with the time required to transport it between stations. For reasons of policy we have never attempted to observe from a tripod lowered from the truck bed so at every station the instrument is removed from the truck and set on three small stakes driven into the ground to serve as a convenient support. This proce-

dure adds some to the labor involved but is a negligible factor in the over-all speed of operation. As illustrative of the speeds which are obtainable, a single instrument with operator and one helper has observed over 100 stations with 1 mile spacing in an eight-hour period although, of course, normal operation would be less than half that number.

Since 1936 more than 200,000 stations have been observed by the Gulf gravimeters and statistics on these routine data indicate that the probable error of a single observation is a little less than 0.05 mg. For example, a set of data obtained in Kuwait, Arabia, where the operator repeated certain stations twenty or thirty times during several months, shows a probable error of a single observation of 0.04 mg. and the distribution follows a typical probability curve. These operations were under rather adverse conditions. Other examples taken at random from routine field data but under more favorable circumstances show for instance that repeat observations involving two different instruments on a group of 15 or 20 stations resulted in a maximum difference of 0.1 mg., a mean deviation of 0.04 mg., and a probable error of a single observation of 0.02 mg. A second group of stations showed a maximum difference between observations of 0.08 mg., a mean deviation of 0.03 mg., and a probable error of 0.02 mg.

It is of interest to note that the accuracy of gravimeters is sufficient to permit their use in obtaining gradient values comparable in accuracy to the torsion balance. Thus an array of three gravimeter stations forming a right angle with legs only 300 feet in length if observed with a readily obtained prevision of 0.02 mg. will provide a gradient measurement equal in accuracy to that obtainable with the torsion balance having a probable error of $4e$. For certain special problems we have used the gravimeter in this manner with good success.

ACKNOWLEDGMENTS

I wish to thank Dr. P. D. Foote and Dr. E. A. Eckhardt of the Gulf Research & Development Company for permission to publish this paper. Also to acknowledge here the excellent development work of the late Dr. Archer Hoyt, who devoted his entire time to this problem, his assistant A. Carnvale, and G. W. Rusler to whom was assigned the bifilar instrument problem and worked jointly on the mechanical features common to both instruments, also others of the staff who had a common interest in the problem.

THE GULF UNDERWATER GRAVIMETER*

T. B. PEPPER†

ABSTRACT

A brief description of the Gulf underwater gravimeter is presented showing the salient design features whereby a regular Gulf gravimeter is incorporated in a device permitting precision gravity measurements in coastal waters several hundred feet in depth.

The instrument is adapted to be lowered to the bottom on a cable and through remote control devices all necessary adjustments are made from the surface. The reading is obtained photographically on a continuously moving film which permits accurate observations even when moderate seismic disturbances cause oscillation of the index point.

In the last decade, as existing oil-producing areas have encroached steadily upon the water bodies of the Gulf Coast and other territories, the necessity of prospecting in areas covered by water has been keenly felt by most of the oil companies. As a result various prospecting methods have been tried with varying amounts of success. Seismograph operations under such conditions proved to be successful from the start but rather laborious and slow for reconnaissance work.

Pendulums and gravimeters were not particularly adaptable in areas covered by water because of the nature of the instruments which require a relatively firm support, and particularly pendulums whose accuracy is very seriously impaired by excessive seismic disturbance. The Gulf gravimeter, while not affected by the adverse conditions as seriously as pendulums, was nevertheless affected to the extent that it was difficult to read unless mounted on a rather firm foundation or tripod.

By a system of two tripods, one for the operator to stand on and one for the gravimeter, it was possible to make observations on calm days in water up to eighteen feet in depth. But when the water was rough it was necessary to observe for a few hours to get a satisfactory reading if, indeed, any was obtained. When obtained, however, the accuracy of the observations was better than 0.1 milligal as proven by repeat observations. The task of setting these tripods, each of which weighed 1500 lbs was done by derricks on barges and was slow, making the entire operation quite costly.

It was evident that operations could be simplified and conse-

* Presented at the Annual Meeting, Chicago, Ill., April 9, 1940.

† Gulf Research & Development Company.

quently expedited if an instrument could be designed to operate on the bottom instead of on tripods and that the savings effected by increased speed of operations would justify a comparatively large expenditure for such an instrument.

Many schemes for attaining such an end were suggested and considered. Some of the most promising ones are listed:

(1) Bell or housing containing the operator and instrument.
(2) Submergeable barge unit containing only the instrument.
(3) Pressure housing type; instrument to be leveled directly by gravity; all other controls to be either automatic or manipulated by remote control from the surface.
(4) Same as (3) except that the instrument is to be leveled by remote control through the use of level indicators.

Also combinations of any of the above, as well as one which had the leveling mechanism outside of the pressure housing.

In judging the schemes just mentioned, cost, simplicity, safety, ease and speed of operation, weight, and durability were kept in mind.

The first scheme, utilizing a diving bell containing operator and instrument was rejected because it had none of the qualities desired. The only reason it was considered at all was that on first thought it appears to be the most direct solution until further consideration shows clearly the details and hazards involved.

The second scheme, utilizing a submergeable barge containing the instrument only, eliminated the hazards of using a diving bell and obviated the necessity of unloading and loading on board a boat, but added the complication of submerging and raising the barge. However, it did not present much promise for speed, and had all of the problems of schemes (3) or (4) which involve a pressure housing with remote controls.

The third scheme, involving an instrument leveled directly by gravity and enclosed in a pressure housing solved the problem of leveling, but since it was considered necessary to know with certainty whether the instrument was level or not, it gave promise of being as complicated as one leveled by remote control. Additional complications were involved in damping oscillations of the instrument in the pressure housing and clamping it while moving from one location to the next. Also it would involve considerable weight because of the space necessary for the damping mechanism. If a liquid was used for

damping, there would always be the possibility of getting it on the optical system and other delicate parts. If electro-magnetic damping was used, there would be the possibility of stray magnetism affecting the operation of the instrument since parts of it are affected by strong fields.

The fourth scheme, involving an instrument enclosed in a pressure housing and leveled by remote control, had possibilities of being the

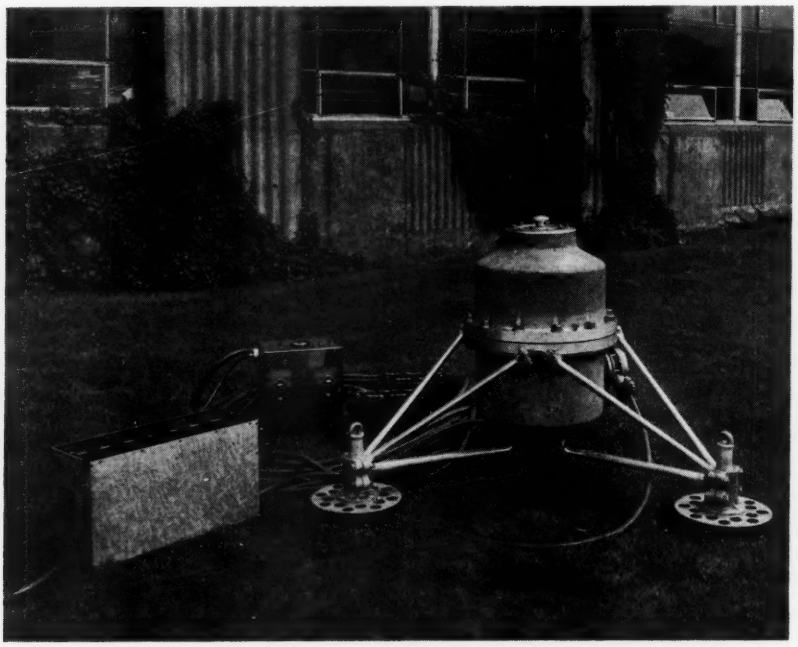

FIG. 1. Gulf Underwater Gravimeter sealed with all control equipment necessary to operate.

lightest of all systems excepting the one with the leveling mechanism outside of the pressure housing. Protection afforded the leveling mechanism when placed inside of the pressure housing was considered an advantage which more than offset the disadvantage of added weight. Since this arrangement came closest to satisfying all requirements, it was chosen as the type to be built.

Before an instrument could be designed along these lines a device was required which would indicate the level position to within less than 10 seconds of arc (see Fig. 2). A very durable combination was

devised which utilized a level vial in combination with photo-voltaic cells with no amplification. In this combination one cell is used on each end of the vial to compensate for light-source voltage fluctua-

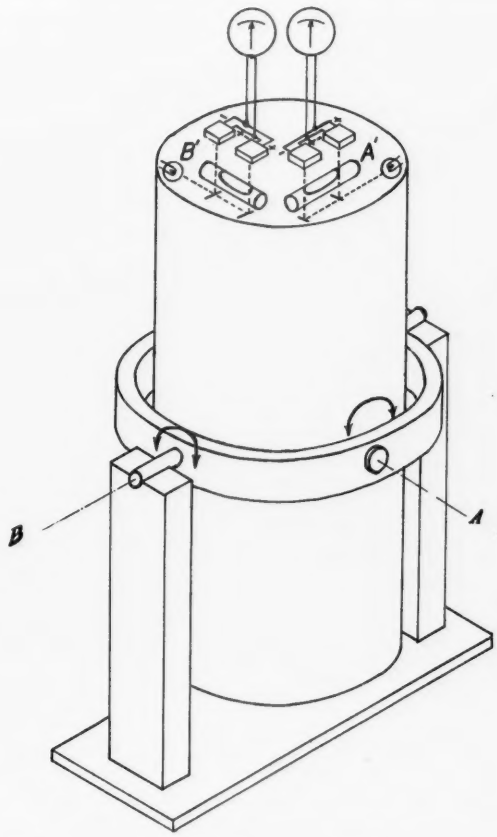

FIG. 2. This sketch shows the relation between level indicators and the axes about which the instrument is revolved to level it. Vial B′ is independent of the state of level on A′ and will not be affected if the level of A′ is changed. A′ will be affected if B′ is changed to greater or lesser degree dependent on how much the instrument is tilted.

tions. The cells are connected in parallel but in such manner as apparently to short each other, i.e., positive to negative, and leads are run from the junctions to a 25-0-25 micro amp. meter. Illumination for both ends of the vial is from a common source. When the meter indicates zero, the instrument is level. At the zero position on the micro-

ammeter, no appreciable change is noted when the light source voltage is varied from zero to any voltage the lamp is able to withstand. This system has a sensitivity of about 3 seconds of arc per micro-ampere on the most sensitive portion of the indicator response-curve with about -10 to $+10$ micro-amps. total deflection when 8 volts is im-

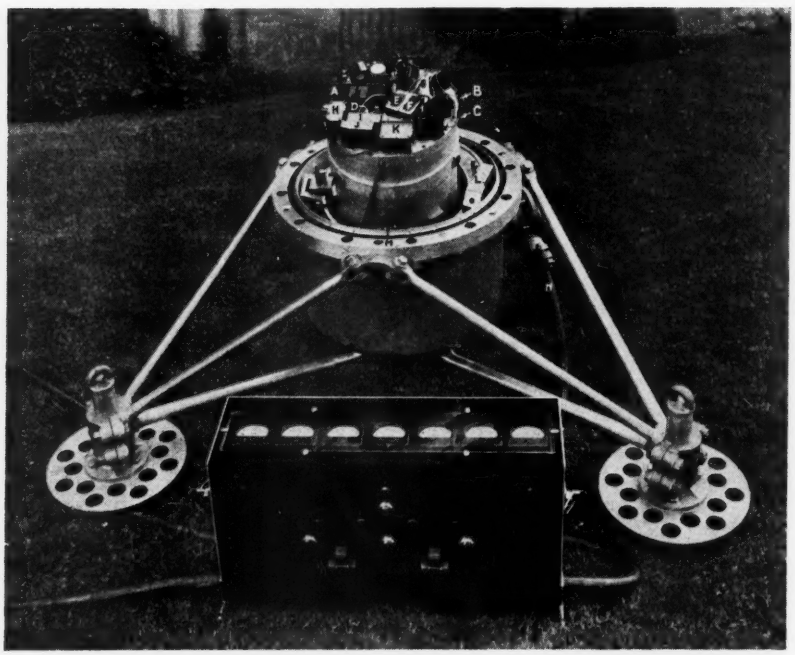

FIG. 3. Gulf Underwater Gravimeter with the top half of the pressure housing removed showing the top-plate assembly and leveling mechanism. Size of available electric motors and other essentials almost proved to be a limiting factor on the size of the unit.

pressed on the lamp. The unit indicates the direction off level even when it is out of level more than 40°; a feature of considerable importance.

Leveling is accomplished by a motor-driven gimbal arrangement in which the two components of leveling motion are sufficiently independent to permit leveling both directions simultaneously. For this purpose a compact arrangement is used in which the maximum leverages are obtained in a minimum space (see Fig. 3). B and C are light sources for the level units. *D*, *E*, *F*, and *G* are photo-voltaic cells which are part of the level indicator system. *L* is the motor drive for one component of level and *M* is its associated leveling unit.

The maximum available leveling motion is 15° off center in any direction. To tilt from 15° in one direction to 15° in any other direction requires less than three minutes including time for all minor adjustments.

In order to appreciate the precision with which the leveling motors have to be stopped it need only be noted that each revolution of the motors represents three seconds of arc, and that on high speed they run at approximately 15,000 RPM. On fine adjustments they must operate at less than 10 RPM. The motors used for this purpose are permanent magnet miniature-train motors which while admirably suitable in other respects unfortunately have low starting torque, a characteristic which complicated matters and necessitated the design of a motor driven contactor device with variable duration of contact. Electrical impulses from these contactors jerk the motors for a small and definite part of a revolution per contact closure. With this sort of a device it is possible to level the instrument while making a record without destroying the accuracy of observation.

The level mechanism is so constructed that it has less than one second back lash, i.e., when the controls are reversed, there is less than $\frac{1}{3}$ turn of the motors before the level starts changing. If the instrument is tilted more than the leveling mechanism can handle the motors move the leveling mechanism until 15° off center is reached. At this limit a contact is made with a circular contact ring thus operating a relay turning off the level motors. In order to make the motors operable again it is necessary to press a button (center top on control panel) continuously and run the motors in the reverse direction to bring it again within the 15° circle.

Clamping the moving system of the gravimeter is accomplished by a permanent-magnet motor, J, working through a gear box, K. Warning signals are actuated by a contact on the clamp shaft which operates a relay on the operator's control panel. The relay turns on a red pilot lamp (center bottom of the control panel), when the instrument is unclamped and a green one (center top) only when it is clamped completely.

Recording is accomplished by photographic means on 35 mm. film. It is of the continuous type and provides a complete record of the instrument deflection from the time the moving system is unclamped until it is again clamped. Accuracy of recording in spite of possible film shrinkage in processing is obtained by fiducial lines photographed simultaneously with the images used for recording gravity. These

fiducial lines are put on the record from the back side of the film while the gravity indications are photographed from the front. Film is drawn through the camera by a permanent-magnet motor, I, driving through a 27,000 to 1 worm gear train, *H*, which builds up sufficient friction to stop the motor when the end of the film is reached. An ammeter in this circuit indicates an increase in current at the control panel, informing the operator that the film is all used. The camera, *A*, which is a remodelled Leica, can then be removed and reloaded when the instrument is brought on board the boat. Film moves through the camera at about $\frac{3}{8}''$ per minute and, assuming observations of seven-minutes' duration, about ten observations can be made on a standard 18-exposure film. Each record is positively identified at the time recording is started by telegraphically coding the fiducial light source.

To facilitate operation a hand hole is provided in the top of the pressure housing for removing the camera, changing lights, and making other routine adjustments. The hand-hole cover can be removed in less than one minute, thereby avoiding breaking of the main seal for all but major adjustments.

A water alarm comprising a ball float in a sump is provided to inform the operator if water is getting into the container. This ball float closes a contact which turns on a red light on the right side of the control panel. The instrument is further protected against damage from leaks at both the hand hole and main seals by a spun aluminum water-deflector which fits inside the upper half of the pressure housing. Holes are drilled in the lower half of the housing to permit any leakage water to run to the sump in the bottom without dropping on any of the mechanism.

The gravimeter used for the under-water unit is a standard Gulf instrument in almost every respect and can be converted to a land unit in less than one-half hour by merely taking it out of the pressure housing and placing it in a land-conversion mounting which includes a different top plate and a mounting assembly with hand-operated leveling screws. The main deviation from the standard land unit is the thermal insulation which is about two times as efficient. While this improvement provides a relatively small decrease in over-all bulk of a land instrument, a net saving of 200 to 300 lbs. was made in the weight of the underwater instrument by this change.

The underwater assembly is constructed mostly of aluminum, weighs about 300 lbs. out of water and 25 or 30 lbs. under water. By

making the unit almost buoyant it is possible to place additional weight where it is needed to produce the greatest stability under water. Three hundred and fifty pounds of lead weights are fastened to the tubular supporting structure for under-water use. This additional weight can be quickly removed when it is desirable to carry the instrument to a land subbase. It can be easily carried by three men when the weights are removed.

The pressure housing is strong enough to withstand the collapsing

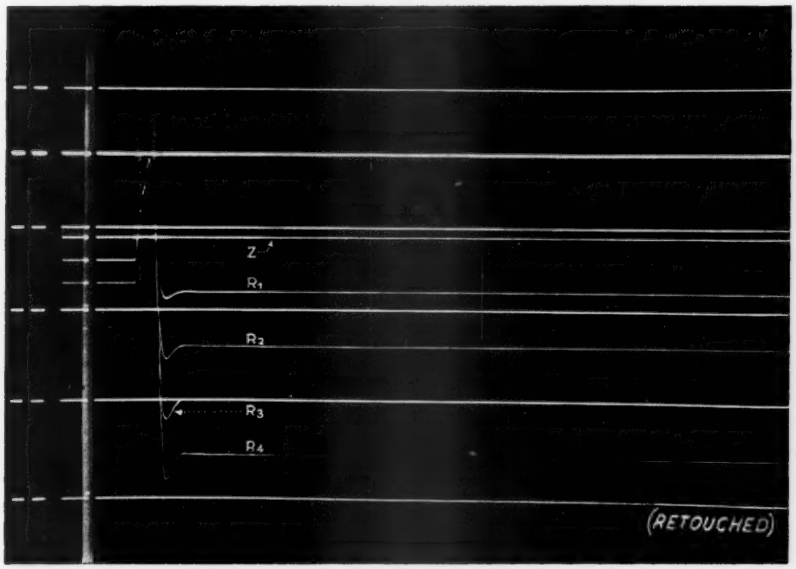

FIG. 4. Illustrating a record taken in quiet water. Note the telegraphic identification on the left.

pressure of a 700 foot head of water, is made of an aluminum alloy, bolted together with stainless steel bolts and corrosion protected by zinc washers.

The control unit contains seven meters, four pilot lights, nine switches of various descriptions, two relays, and two motor driven contactors for fine adjustment of the level mechanism. Meters are mounted horizontally in line on the top of the control unit to give the minimum disturbance with rolling and pitching of the boat and are covered with a sealed-in plate glass window to protect them from water damage. Switches and other controls are on the vertical front panel

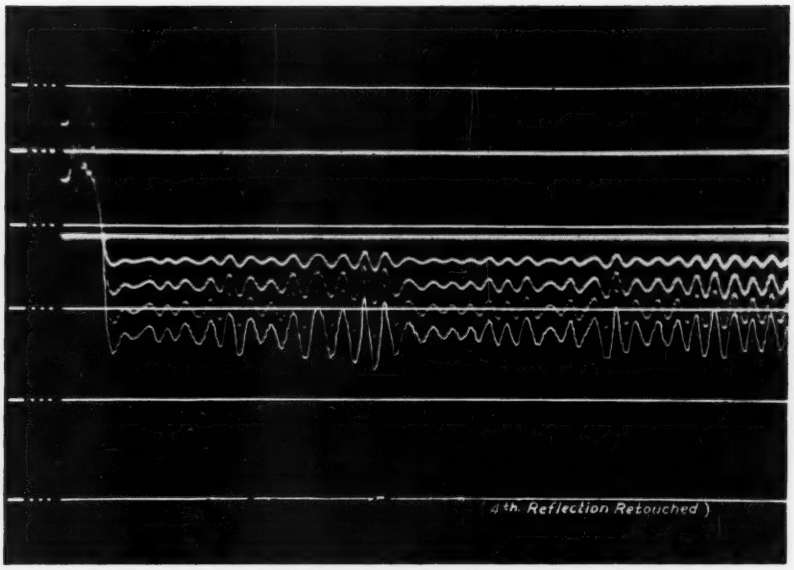

FIG. 5. This record was taken in rough water and is considerably poorer than the average record although it can still be read to 0.1 to 0.2 mg.

which is protected by a cover sealed with a rubber gasket when not in use.

There is positive indication in the control unit of every step and of the operability of every piece of apparatus involved in taking an observation so that the operator has full knowledge of instrumental conditions at all times. Thus inadvertent damage to the apparatus due to the remote control operation is minimized.

Power is supplied to the control panel by two 12-volt storage batteries. An additional 12-volt battery is used to maintain the temperature of the gravimeter, which is controlled to a thousandth of a degree over short time intervals and a few hundredths of a degree over long time intervals.

In order to handle all of the controls and safety devices, a nineteen conductor electrical cable, *N*, Fig. 3, connects the control cabinet to the gravimeter. Four of the conductors are used for a common ground but provide one or more spare conductors in case of damage to other wires; the remaining 15 conductors control: 4 motors (3 of which are reversible), 3 separate light-source circuits, thermostatic heat control, 15°-limit control, water alarm, clamped signal, and two photo-cell circuits which do not use the common ground.

FIGS. 6 and 7 are pictures taken of actual operation in the Gulf coast. In Fig. 7 the instrument is being lowered into shallow water in order that it may be carried to a land subbase to tie water data to adjacent land data. The hoist assembly operated by power take-off from the boat engine is clearly shown.

There are no relays in the gravimeter housing, all circuits being controlled directly from the control unit. There are, however, a total of three relays in the setup, one for the heat control, another for the clamped-unclamped indicator and the third for the 15°-limit control all in the control unit and associated parts.

Records are read by a special micrometer slide-comparator in much the same fashion as the gravimeter is read directly by a micrometer eyepiece. The advantages of continuous photographic recording for this work are obviously its simplicity and the permanence of record, but more important is the fact that even though the instrument never comes to rest, a fairly good gravity value can be obtained by special reading procedure. Records are corrected for film shrinkage errors by reading the fiducial lines previously mentioned and correcting the values accordingly.

Fig. 4 shows a typical record in quiet water. The heavy lines are fiducial lines. Line marked *Z* is the zero line. Relative gravity can be computed by measuring the distance between the "zero" and any line, *R*, and multiplying by the proper conversion factor or constant. This record can be read with an accuracy of about .02 milligals. Whether or not the gravity value is good to that precision will depend to a great extent upon the drift curve.

Fig. 5 illustrates a record taken in rough, shallow water. Proper reading of this record should give a gravity value with a probable error of 0.1 or 0.2 mg.

A maximum of 17 stations per day has been taken to date with an average of 6 stations per working day. The principal causes of delay in this type of work are unfavorable weather conditions and the slowness of boat transportation.

Another handicap due to the relatively slow speed of boats is the time consumed in travel between the scene of operations and headquarters. While this handicap can be overcome to some extent by providing mobile quarter-boats for the crew, it is evident that work of this type can never attain the speed of land operations.

ACKNOWLEDGMENTS

In concluding this brief discussion of the Gulf underwater gravimeter the author wishes to acknowledge the co-operation of G. B. Lamb, Anthony Carnvale, W. G. Darrall, and others; also to thank Dr. E. A. Eckhardt and other officials of the Gulf Research & Development Company for permission to publish this paper.

THE EFFECT OF DENSITY ON SEISMIC REFLECTIONS*

S. S. WEST†

ABSTRACT

By means of existing data on the density of rocks, it is shown that reflection coefficients of seismic waves, calculated from velocities alone, often differ greatly from the actual values. Data on a large number of density discontinuities have been tabulated, and the true reflection coefficients calculated for six cases in which velocities are also known.

The reflection of sound waves at discontinuities in the earth, upon which the art of seismic prospecting is based, has nearly always been treated as though only the discontinuous change of the velocity were of any importance. The assumption was convenient in that it freed the geophysicist of the necessity of much tedious measurement, but it was certainly not a good approximation. The purpose of this paper is to point out that changes of density can be quite as important as changes of velocity in the production of seismic reflections and that therefore the empirical correlation of reflections with abrupt changes in the velocity-depth curve may sometimes lead to serious errors.

The ratio R of the amplitude of the reflected wave to that of the incident wave for normal incidence at a plane interface is given by the well-known formula

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

where ρ is the density of the medium and V the velocity of the longitudinal wave. The index 1 refers to the medium in which the incident and reflected waves are propagated (upper stratum in our case) and the index 2 to the medium beyond the interface (lower stratum). The sign of this expression gives the phase of the reflected wave, for, when $\rho_2 V_2$ is greater than $\rho_1 V_1$, a compression is reflected as a compression, and, when $\rho_1 V_1$ is greater than $\rho_2 V_2$, a compression is reflected as a rarefaction. Thus the first motion of the ground at the seismometer will be up when $\rho_2 V_2$ is greater and down when $\rho_1 V_1$ is greater. The

* Presented at the Annual Meeting, Chicago, Ill., April 9, 1940.

† Joint Geophysical Laboratory of Stanolind Oil and Gas Company and Western Geophysical Company.

assumption of normal incidence is close enough to actual conditions to be a satisfactory approximation.

The longitudinal velocity V is given by

$$V = \left(\frac{\lambda + 2\mu}{\rho}\right)^{1/2}$$

where λ and μ are the Lamé constants. If we assume a fixed value of Poisson's ratio σ, then λ is proportional to μ and $V = k(\mu/\rho)^{1/2}$, where k is a constant. This assumption is justified by the fact that σ changes slowly in the earth, approaching the value $\frac{1}{4}$ at large depths. In this latter case we may write the formula for the reflection coefficient R as

$$R = \frac{(\rho_2\mu_2)^{1/2} - (\rho_1\mu_1)^{1/2}}{(\rho_2\mu_2)^{1/2} + (\rho_1\mu_1)^{1/2}}$$

where μ is the rigidity of the medium in question.

Although we have usually to do with ρ and V in practice, a classification of discontinuities with regard to ρ and μ gives a clearer idea of the geological conditions which define them. In this system the following eight types yield reflections.

1). $\rho_2 > \rho_1$, $\mu_2 > \mu_1$ (V_2 nearly the same as V_1). This is one type of true density discontinuity when $V_2 = V_1$, $\mu_2/\rho_2 = \mu_1/\rho_1$. It may occur when induration increases both density and rigidity. First arrival is upward, i.e., phase is unchanged by reflection.

2.) $\rho_2 > \rho_1$, $\mu_2 = \mu_1 (V_2 < V_1)$. Probably not a very common case and not productive of large reflection coefficients when it does occur. First arrival is upward (phase unchanged).

3.) $\rho_2 > \rho_1$, $\mu_2 < \mu_1 (V_2 < V_1)$. This yields an unusually large velocity discontinuity, but a small reflection coefficient. It can occur with salt on anhydrite, or possibly in a homogeneous medium in which there is a zone of saturation by fluid which increases the density of the saturated medium. First arrival upward or downward, or no reflection.

4.) $\rho_2 = \rho_1$, $\mu_2 > \mu_1 (V_2 > V_1)$. The commonly assumed true velocity discontinuity. First arrival upward (phase unchanged).

5.) $\rho_2 = \rho_1$, $\mu_2 < \mu_1 (V_2 < V_1)$. The inverse of type 4. First arrival downward i.e., phase reversed by reflection.

6.) $\rho_2 < \rho_1$, $\mu_2 > \mu_1$, $(V_2 > V_1)$. The inverse of type 3. First arrival upward or downward, or no reflection.

7.) $\rho_2 < \rho_1$, $\mu_2 = \mu_1$, $(V_2 > V_1)$. The inverse of type 2. First arrival downward (phase reversed).

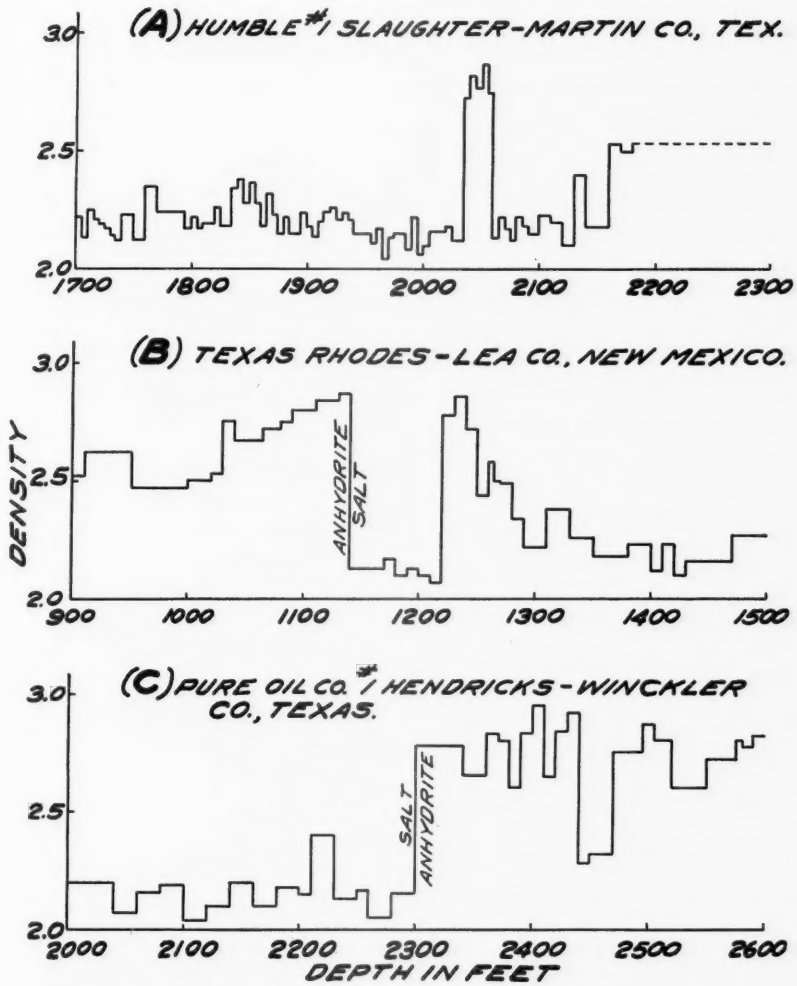

FIG. 1. Portions of density logs which contain discontinuities of density sufficiently large to produce strong reflections or to modify greatly reflections from discontinuities of velocity at the same depths.

8.) $\rho_2 < \rho_1$, $\mu_2 < \mu_1$ (V_2 nearly the same as V_1). The inverse of type 1. First arrival is downward (phase reversed).

The data needed to illustrate these types of discontinuities are quite rare and hard to procure, but useful information can be obtained from several sources. Mr. R. C. Coffin of the Stanolind Oil and Gas Company has kindly provided density logs of ten wells located near the

TABLE 1

MAJOR DENSITY DISCONTINUITIES FROM MEASUREMENTS ON CUTTINGS FROM WELLS

Location of Well	*Depth*	*Density*		*R (%)*
		Upper	*Lower*	
Pure Oil Co. #1 Hendricks Winkler Co., Texas	2300 2440	2.15 2.92	2.78 2.28	12.8 −12.3
Texas-Rhodes Lea Co., N. M.	1140 1220	2.87 2.07	2.12 2.78	−15.0 14.7
	1600 1620	2.75 2.15	2.10 2.85	−13.4 14.3
	1640 1720	2.87 2.22	2.36 2.76	− 9.8 9.0
	1750 1940	2.18 2.11	2.65 2.77	9.7 13.5
	1980 2000	2.18 2.62	2.66 2.13	9.9 −10.3
	2265 2300	2.25 2.45	2.74 2.89	9.8 8.2
	2390 2460	2.82 2.13	2.22 2.84	−11.9 14.3
	2500 2685	2.82 2.17	2.12 2.60	−12.2 9.0
Carter-Zweibel Andrews Co., Texas	1460 1565	2.57 2.23	2.23 2.98	− 9.2 14.4
	1870 1895	2.43 2.93	2.93 2.45	9.3 − 8.9
	1985 2195	2.18 2.17	2.63 2.87	9.4 13.9
	2235 2760	2.17 2.08	2.94 2.82	15.1 15.1
	2780	2.82	2.23	−13.7
Marland-Zock #1 Guitar Howard Co., Texas	1215 1700 2270	2.80 2.33 2.30	2.28 2.93 2.80	− 9.8 11.4 9.8
Humble #1 Slaughter Martin Co., Texas	2035 2060	2.12 2.76	2.72 2.13	12.4 −12.9
	2605	2.20	2.78	11.6
	2980	2.32	2.76	8.7

TABLE 1

Location of Well	Depth	Density		R (%)
		Upper	Lower	
Texas-Lockhart	1660	2.92	2.32	−11.4
Lea Co., N. M.	1910	2.96	2.42	−10.0
	1990	2.42	2.95	9.9
	2020	2.95	2.32	−12.0
	2410	2.68	2.22	− 9.4
	2620	2.38	2.82	8.5
	2650	2.94	2.27	−12.9
	2780	2.32	2.74	8.3

southeast corner of New Mexico. The density of the cuttings of these wells was carefully determined for each five-foot or each ten-foot section to depths of three to five thousand feet, the measurements being made by means of a Jolly balance with the sample submerged in oil. Seven of these logs show large variations in density, and from these a reflection coefficient $R=(\rho_2-\rho_1)/(\rho_2+\rho_1)$ was computed for each discontinuity. (By assuming equal velocities to calculate this reflection coefficient we depart somewhat from physical reality, but the coefficient thus obtained is a convenient measure of the magnitude of the discontinuity of density. The true reflection coefficient is calculated later for those cases where the velocities are known.) In these seven wells there were 112 discontinuitities with $|R|>5\%$, 63 positive and 49 negative. The data on those with $|R|>8\%$ are listed in Table 1.

In some of the cases listed, the thickness of the bed below the discontinuity might not be great enough to permit a good reflection, but

TABLE 2

DENSITIES FROM GRAVIMETER MEASUREMENTS

Location	Formation	Density
1. Caddo and Washita Counties, Okla.	Quartermaster (red shale and sandstone)	2.4
	Cloud Chief (gypsum)	2.7
	Day Creek-Whitehorse (dolomite)	2.1
2. Carter County, Okla.	Trinity sandstone	2.1
	underlying Permian	2.4
3. Llano Estacado escarpment, N. M.	above escarpment	2.0
	below escarpment	2.4

in Fig. 1 are shown portions of the logs in regions where the formations are thick and the density differences large. The boundaries of the salt section are shown on the logs in Fig. 1B and 1C. Data from "well-shooting" in Gaines County, Texas, (about 50 miles away) indicate that the velocity in the layer above the salt is about 12,000 ft./sec., in the salt about 15,000 ft./sec., and below the salt about 11,000 ft./sec.

From a paper by L. L. Nettleton[1] we take the densities of adjacent

TABLE 3

REFLECTION COEFFICIENTS CALCULATED FROM BOTH DENSITY AND VELOCITY

Location	*Formations*	*Densities*		*Velocities*		*Reflection Coefficient*		$\frac{\mu_2}{\mu_1}$	*Type of Discontinuity*
		ρ_2	ρ_1	V_2	V_1	*Actual*	*Equal Densities*		
Texas-Rhodes Lea Co., N. M.	Anhydrite Salt	2.12	2.87	15,000	12,000	−3.9%	11.1%	1.2	6
	Salt Anhydrite	2.60	2.17	11,000	15,000	−6.4	−15.4	0.6	3
Pure Oil Co. #1 Hendricks Winckler Co., Texas	Anhydrite Salt	2.52	2.85	15,000	12,000	5.0	11.1	1.4	6
	Salt Anhydrite	2.78	2.15	11,000	15,000	−2.5	−15.4	0.7	3
Caddoand Washita Cos., Okla.	Quartermaster Cloud Chief	2.7	2.4	9,000	8,300	10.0	4.0	1.3	1
	Cloud Chief Day Creek	2.1	2.7	11,000	9,000	−2.5	4.0	1.2	6

strata which are listed in Table 2. For the first three formations it is possible to estimate velocities from the shot point seismometer breaks of seismograph records made in that region. Where the formations are deeply buried the velocities will be greater, but their ratios (and the ratios of the densities) will probably be much the same. The velocity thus obtained for the Quartermaster formation is 8300 ft./sec., that for the Cloud Chief is 9,000 ft./sec. and that for the Day Creek is 11,000 ft./sec. Of the other two pairs of formations, it can only be

[1] "Determination of Density for the Reduction of Gravimeter Observations"; GEOPHYSICS, Vol. IV, No. 3 (1939) p. 176.

said that the assumption of equal velocities gives them reflection coefficients of 7% and 9%, respectively.

Six discontinuities are sufficiently well described by the above data to permit the calculation of the true reflection coefficients and comparison with reflection coefficients from the assumption of equal densities. Table 3 contains the data and the results of these calculations. The ratio μ_2/μ_1, which is necessary for the classification of the discontinuity, is given by

$$\frac{\mu_2}{\mu_1} = \frac{V_2^2\rho_2}{V_1^2\rho_1}.$$

Thus, in five of the six cases we have been able to investigate the effect of the change of density has been to reduce the amplitude of the reflection so much as to make it scarcely detectable, and in the first and last cases the phase is reversed. One case (fifth line of Table 3) is a true density discontinuity of type 1, which type should be fairly common, since rocks often become more rigid as they become more dense, and conversely. The occurrence of types 1 and 8 especially needs investigation, for they produce reflections very difficult to correlate with velocity data.

It will therefore be seen that one must take account of density as well as velocity in any quantitative consideration of seismic reflections. The expense of obtaining density data should not be great where access can be had to cuttings from one or two wells in the neighborhood of a prospect, and geological and velocity data can be obtained from the same wells. In this way reflections can be assigned to geological interfaces much more definitely than has hitherto been possible. Further research on the problem should yield results of considerable value for the interpretation of the field data of seismic prospecting.

RESOLUTION CONTROL IN SEISMIC SURVEYS*

ROLAND F. BEERS†

ABSTRACT

Development of the concept of velocity stratification by experimental means has revealed the origin of certain reflection horizons. Correlation of these data with subsurface lithology suggests a method of attack, employing seismic means, on the problem of the stratigraphic trap.

This paper outlines the problem and describes a method whereby stratigraphic relationships may be measured. It is suggested that a seismic wave may be fitted to the task by altering its wave length in accordance with the degree of resolution desired. Experimental examples of the procedure are given.

Field experiments tending to develop the concept of velocity stratification have disclosed details of sedimentary stratigraphy which are of value in allocating sources of seismic reflections. As mentioned in a previous paper[1] these reflections are found to originate in stratified media where a sudden change in seismic properties is encountered in the path of a seismic wave. These discontinuities may be of one or more of several types. Included among them will be found sudden changes in density, modulus of elasticity, velocity of propagation to longitudinal waves, and acoustic impedance. These properties of rocks *in situ* are susceptible to direct measurement by experimental means. The results of these measurements yield stratigraphic logs which are valuable for the purpose of correlation between different locations where bore holes have been drilled and analyzed experimentally.

In addition to the function of correlation these measurements yield detailed information regarding the nature and properties of rocks encountered in the path of the seismic waves. This paper is primarily concerned with the distribution of these properties throughout the geologic column and the discussion of problems of correlation for which a solution may be available as a result of these studies.

One of the most frequently occurring interfaces where good quality reflections have been observed is that of a limestone overlain by shale. The magnitude of seismic discontinuity at such a plane as determined from measurements will produce a computed reflection coefficient

* Presented at the Annual Meeting, Chicago, Ill., April 9, 1940.

† The Geotechnical Corporation, 1702 Tower Petroleum Bldg., Dallas, Texas.

[1] Roland F. Beers, GEOPHYSICS, Vol. V, No. 1, (1940), pp. 15–21.

between 0.15 and 0.30; a reflection of this order is usually an outstanding or "dominant" reflection of a record. Reflection coefficients of lesser value down to 0.10 are discernable and frequently offer support to the correlation pattern in their interval relationship to other "dominant" reflections. Supporting theoretical considerations, it is not infrequent that good quality reflections are found at the interface separating a shale overlain with limestone. In general, coefficients of this class have not been observed to be as large as those of the inverse sequence mentioned above. There is an interesting relationship between two consecutive reflections, the first from a shale to limestone interface, the second from limestone to shale. Examples of this reflection pattern are frequently observed in beds of Devonian to Ordovician age, such as are exemplified in and near the Seminole Plateau District of Oklahoma. This province is characterized by dominant reflections from or near the top of Hunton Lime, others within or near the base of the Hunton Lime if the limestone section is thick enough, and an additional outstanding reflection from the interface between the Viola Limestone and the overlying Sylvan Shale. For many years mapping of structural details in this province has depended upon the ability of the seismic interpreter to follow accurately the correlations of reflections from each of these stratigraphic positions. Not infrequently the intervals between adjacent reflections in this section undergo wide changes. These changes may have been caused by changes in the amount of deposition of the formations or by removal by erosion from the top of the formations. Intimately related to the problem is the influence of the Woodford or Chattanooga Chert which is frequently the beginning of a series of reflections of equal dominance spaced at equal intervals from one another.

The approach to this intricate stratigraphic problem has often been by the route of fortuitous circumstances, although Morris Muskat has shown analytically the relationships which control the reflection wave patterns in the three-layer problem.[2] It has been observed by many that the ability of the reflection seismograph to resolve the stratigraphy of this province into an orderly array has been affected profoundly by the circumstances surrounding the shot hole. In many instances reflection correlation profiles have been repeated again and again with the hope of obtaining just that particular character of record which would enable one to "see" clearly the exact stratigraphic

[2] M. Muskat, GEOPHYSICS, Vol. III, No. 3, (1938), pp. 198–218.

picture. One common practice employed in the field for influencing the situation has been the depth of shot hole. In some cases it has been found that a shallow hole produces more intelligible results than does a deep hole. On other occasions the reverse has been observed. Faust[3] has made observations on this point.

A simple but valuable concept leading toward an understanding of this problem may be drawn from the field of engineering. Here it is common practice when making a physical measurement to select a measuring device consistent with the dimensions to be measured. In field surveys where a precision of a few feet is satisfactory this practice leads to the use of the transit with stadia wires for dimensions of the order of a fraction of a mile. For finer resolution a steel tape is employed whereby a distance of 100 feet may be measured within a few hundredths of a foot. For instruments of great precision micrometers are employed leading to an accuracy of .001 of an inch. In approaching the problem of stratigraphic analysis it is helpful to consider the length of measuring devices which we might employ. It will be seen that this choice falls naturally upon the wave length of the seismic wave which is to be fitted to the dimensions of the stratigraphic problem.

It has often been customary to speak of seismic waves as having some definite frequency. Considerable effort has been expended in maintaining these waves as recorded on seismograph records within certain frequency limits. It seems likely to be more helpful for these purposes if we abandon this concept and view the reflection phenomenon in terms of the length of time during which the seismic impulse persists. This period of time multiplied by the instantaneous rate of wave propagation through the formation then determines the length of the wave which is at that instant available for measurement of stratigraphic intervals. If we wish to control dimensions of this seismic yardstick we have one variable upon which to operate: the duration of the seismic impulse. It seems possible to control the length of this impulse most effectively at its point of generation, i.e., the shot point. Certain it is that much control can be effected here with beneficial practical results. In the East Texas Basin, for example, the length of this impulse can be varied between limits of 0.02 and 0.04 seconds. This is common knowledge to a great many operators and is repeated here only in order to summarize pertinent information in one place. The

[3] U. S. Patent No. 2,156,624, May 2, 1939.

manner in which this impulse can be varied is determined somewhat by the local conditions. These involve the nature of the soil, the depth to the water table, and the bed rock at the base of the aerated zone. Considerable effect is also imposed on the recorded seismic wave by the surface and aerated zone, but these effects are separate from those upon the generated wave and will be considered later.

It has been observed in East Texas that a shot located below the top of the unweathered zone, also below the lower surface of ground water, will generate an impulse whose duration is close to the lower limit mentioned above. If the shot is pulled up into the main body of ground water the duration of the impulse will be lengthened, and the longest impulse of all will be generated when the shot is located just above the top of the water stratum, usually within the weathered zone. Unfortunately a shot located in this last mentioned position produces an undesirable ground wave of long duration and large amplitude. This wave, commonly spoken of as "ground roll," travels horizontally along a path intervening between the shot point and recorder stations and frequently succeeds in completely masking all reflection waves arriving coincident with it. It is customary in such circumstances to space the recorder and shot-point stations at such intervals that reflections may be observed on the record at times when no ground roll is present. In other instances the horizontally traveling wave is diminished in amplitude by the use of high-pass filters or through the use of interference effects between multiple detectors. None of these factors have any bearing on the problem under discussion but they are mentioned in order to eliminate effects which are often considered of importance in handling the present problem. It will be seen that they are irrelevant.

The effect of altering the duration of the impulse generated at the shot hole will depend upon the stratigraphic problem under examination. In East Texas one of the outstanding reflections commonly employed for correlation purposes is the so-called "Georgetown" or "Comanchean." Apparently this reflection comes from more than one interface in the geologic column. When the duration of the generated impulse is short, i.e., of the order of .020 seconds, it is possible to observe the component reflections, one coming from each surface of discontinuity. It will be seen that if the generated impulse could be adjusted to a certain critical length then the reflected components could be made to appear to be one single reflection of extended duration. This process is accomplished by arranging to have consecutive

impulses of such duration and at such intervals as to combine additively in phase, thereby producing a larger amplitude in combination than is possible either as individual pulses, or combined in any other phase relationship. This concept has been supported repeatedly by experimental means. The correct procedure in such a problem depends upon the aim of the survey. If it is desired to map structural details on the top of the Comanchean section without investigating the more minute intricacies of the stratigraphy then the most desirable impulse will be that of long duration. By its use each of the component reflections will add together in favorable phase relationship so as to produce an outstanding reflection of larger amplitude than would be available if the components were separated. For this reason it is common to observe that shallow shot holes in East Texas often produce the clearest results and that many prospects where deep holes have been drilled have been found to be incorrect in their structural interpretation.

If impulses of short duration are employed, the confusion attendant upon correlation efforts becomes very great. This difficulty is often derisively spoken of as the "pulse" problem or the "leg" problem. The number of "legs" with which one has to contend in making an interpretation under these conditions is so great that it is frequently impossible to stay on the same "leg" of a reflection. As a result, mis-correlations frequently follow of the order of at least one "leg." In East Texas this may amount to about 125 feet.

In attacking the stratigraphic problem of the Devonian to Ordovician section of Oklahoma a different situation is often found. Here the ability of the seismograph to follow stratigraphic changes accurately calls for a fine degree of resolution. It is often necessary to know whether or not a reflection is being returned from the Hunton lime. In areas where thick Hunton is present it is necessary to know whether or not two Hunton reflections may be expected. Practical experience has shown that when the Hunton exceeds a thickness of 275 feet it is reasonable to expect one from the Hunton top and one from an interval of 275 or more feet below it. It will also be observed, following this sequence, that there is a reflection from the Viola, which, in the case of very thick Hunton, may be of diminished amplitude. This is believed to occur because of the reduction in the amplitude of the seismic wave transmitted through the thick Hunton section to the Viola top. Frequently an estimate of the presence of the Viola reflection can be tentatively based on this consideration. Under these conditions it is desirable to employ a seismic impulse of as short duration as possible,

consistent with all other requirements. In general the shorter the duration of impulse employed the more intricate becomes the problem of correlation. So many "legs" can be developed on each of the reflections with excessively short impulses that it becomes an intellectual impossibility for the interpreter to keep everything straight. There are so many possibilities of mis-correlation that he becomes hopelessly confused.

This is especially true if intervals occur which change; this is the problem of the stratigraphic trap. To reduce this difficulty, resort has been had in the past to continuous profiling. By this means correlations are established over subsurface intervals of fifty feet in horizontal extent. On the assumption that no extreme changes in depth to a reflecting horizon can occur within this short distance, it is possible to make correlations on continuous profile records from trace to trace. Contiguous records are tied together by at least one overlapping position so that no difficulty is had in correlating from record to record. The only remaining difficulty is then to follow a reflection or series of reflections accurately across each record. If good quality records are obtained and if the resolution in use is well adapted to the stratigraphic problem, then accurate results may be expected.

In this province a good shot hole is said to be one which yields sufficient but not unnecessary resolution. Fortunately this has been the prevailing situation here since the inception of the reflection seismograph. It is interesting to speculate upon the probable development of the seismograph if these fortuitous conditions had not prevailed in this province. This area was literally the cradle of the reflection seismograph; under these ideal conditions many results were obtained of great practical value. This encouragement undoubtedly led to extension of the method to other less favorable areas where progress was made possible only through the faith engendered in proven prospects.

There are many stratigraphic problems which do not yield solutions as easily as the one mentioned above. In some cases it is necessary to lengthen the duration of the seismic impulse generated at the shot point. In others it is desirable to shorten this impulse. Many workers have contributed to this problem and a number of patents have been granted on methods of control. Among those which have been examined by the writer are:

U. S. Patent No. 2,151,878, B. B. Weatherby, 3/28/39,
U. S. Patent No. 2,154,548, B. B. Weatherby, 4/18/39,
U. S. Patent No. 2,156,198, S. A. Scherbatskoy, 4/25/39.

Other workers have undoubtedly observed this phenomenon and have contributed to its development. In general the principles employed are the same and are intended to produce a seismic impulse at the shot point of pre-determined duration. There is also some evidence of intention to shape the impulse, that is, to control the steepness of the wave front. This will be discussed in connection with receiving apparatus and does not produce the same effect as does the control of actual pulse duration.

Some have observed the influence of the dimensions of the shot hole cavity upon the characteristics of the generated wave. J. A. Sharp[4] has outlined the idealized conditions and has observed that the length of the generated wave depends, among other factors, upon the radius of the cavity created by the explosive. This radius is determined by the physical characteristics of the shot hole medium. At the inception of the explosion a wave of spherical dimensions proceeds radially from its source. The explosive wave shatters the medium in its path so long as its force exceeds the "rupture strength" of the material encountered by the wave. The force diminishes as the radius increases in a manner closely resembling the analogous radiation problem, due allowance being made for energy transformation into frictional and heat losses. The wave front finally arrives at some radius where the medium is no longer shattered by the existing force, at which point propagation of the elastic wave takes place. It is the dimensions of the cavity at this instant which determine the wave length and other characteristics of the generated wave. These considerations are affected by water-loading of the shot hole medium and the effectiveness with which the shot is tamped.

The dimensions of the cavity where elastic wave propagation sets in also affect the amplitude to be expected from reflected waves observed at the recorder stations. Assuming that the propagated wave may be considered ideally spherical, it is seen that the amplitude of the reflected wave for a given charge of explosive will be greater, the larger the radius of the cavity at the onset of the elastic wave propagation.

In addition to the influence of the generated wave upon the control of seismic resolution, we have also to consider the characteristics of the seismograph recorder instruments. However these do not control resolution. They may prevent adequate control after it has been

[4] Unpublished manuscript, read at the S.E.G. Annual Meeting, Los Angeles, Calif., March 1937.

established. H. A. Wilson[5] has shown in his very valuable paper the response characteristics of seismographs whose natural period is longer than, equal to, or shorter than the period of ground motion. He has analyzed the response of these instruments when critically damped and when undamped. He makes the observation, "Critically

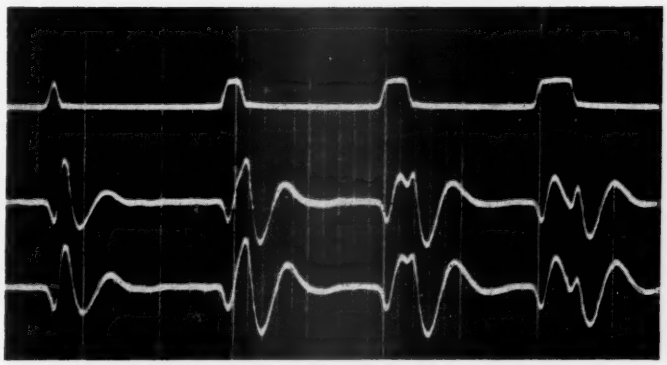

FIG. 1. Response to two successive Heaviside unit-functions of opposite sign, separated by various intervals.

damped seismographs are obviously better when it is desired to observe the arrival of several waves separated by appreciable intervals." This is clearly a contribution to the problem at hand and coupled with adequate control of the characteristics of the generated wave affords practical results which are otherwise unavailable.

Fig. 1 shows a typical response curve taken from a critically damped instrument whose period was greater than the period of the exciting impulse.* The effect of lengthening the duration of this impulse may be noted from the latter parts of Fig. 1. As the natural period of the critically damped instrument is first equalled and then exceeded, it will be noted that the response recorded by the seismograph becomes increasingly complicated. These experimental results

[5] H. A. Wilson, Physics, Vol. 2, No. 3, (1932), pp. 186–199.

* Note on the preparation of these oscillograms: A complete reflection seismograph was set up in the laboratory. The detector was buried in the earth. The moving system of the detector was given a displacement as shown on the first (top) trace of each figure, by means of an electromagnetic force. The magnitude and wave form of this applied force was controlled as shown in the Figures. The two lower traces show the response of a critically damped seismometer.

verify Wilson's analytical derivations and emphasize the importance of fitting the period and damping of a seismograph wave detector to the problem in hand.

These experimental results offer, incidentally, some insight as to

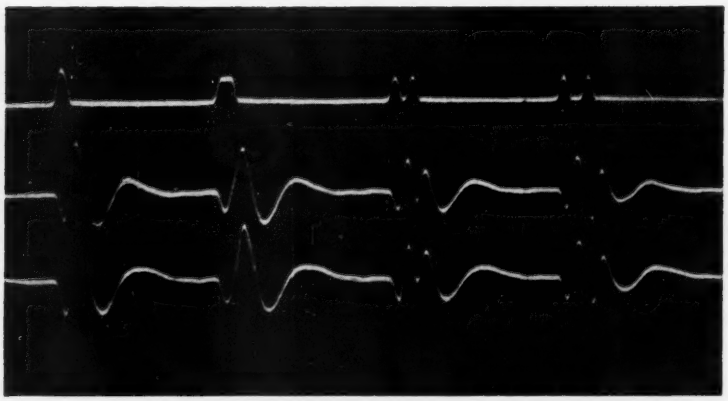

FIG. 2. Response to two successive impulses of same sign.

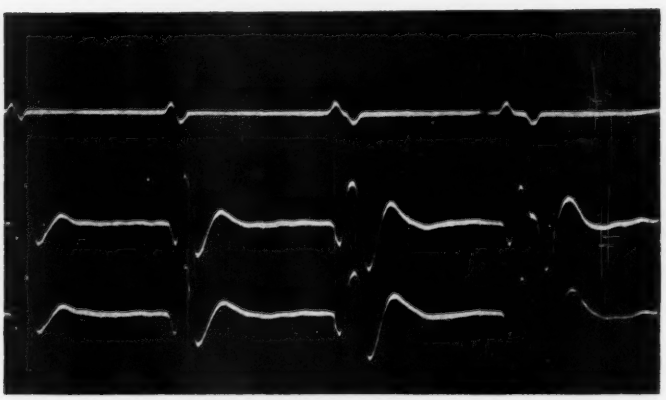

FIG. 3. Response to two successive impulses of opposite sign.

the nature of the impulse which is commonly observed on the reflection seismograph. From an examination of Fig. 2 it will be seen that a single unidirectional impulse produces a response not exactly like the reflection wave. When a positive upward deflection is combined with a negative deflection of equal magnitude, then we observe that

the response of the seismograph approaches that observed in field practice. Records taken in these illustrations were made in the laboratory under ideal conditions so that the results would be free from unwanted interference from other waves.

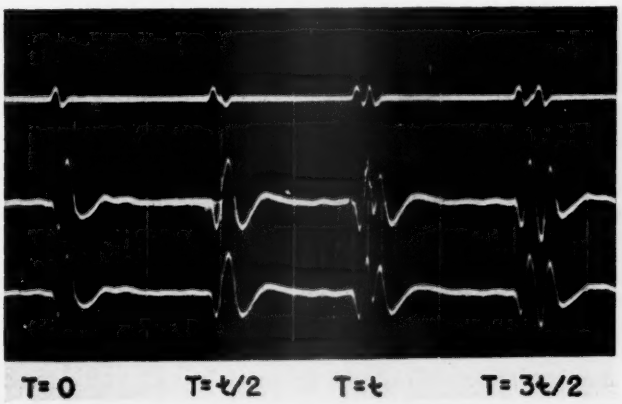

FIG. 4

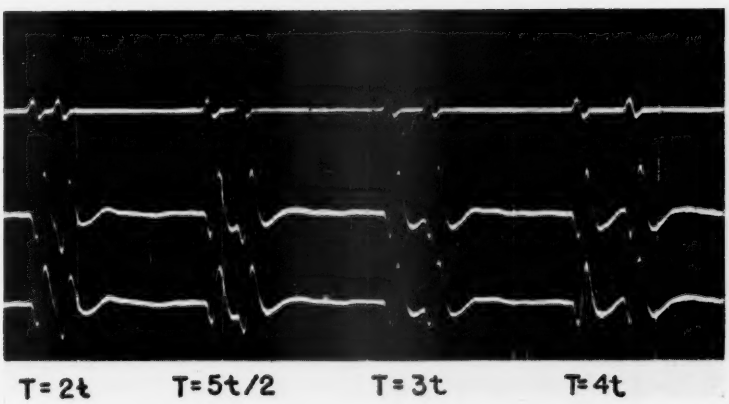

FIG. 5

FIGS. 4 and 5. Response to two successive sine waves, separated by various intervals.

Fig. 3 shows tracings of a more complicated impulse. This consists of a positive displacement of unit value followed in order by a negative displacement of equal value, then at the same interval by an additional negative displacement of unit value, and finally a positive displacement, returning the round to zero position. The wave recorded by the

seismograph for this type of excitation will be seen to be almost an exact reproduction of the customary reflection wave as observed in field practice.

In order to illustrate the influence of control factors upon the degree of resolution attainable, these experiments have been performed with a critically damped instrument of fixed period t. The duration of the exciting impulse has been altered as well as the interval T between two consecutive impulses. Figs. 4 and 5 show the response of the seismograph to a wide assortment of impulse characteristics. An appreciation of the possibilities of the resolution control by these means will be best afforded from a close study of these records.

As reported by Wilson, the critically damped instrument records quite accurately the second derivative of ground motion. Under some circumstances undamped instruments of long period perform similarly. If it is desired to record a series of consecutive impulses it is important that the *period* of the instrument and its *damping* be adjusted in accordance with the duration of impulses to be received and the time interval separating them. It might be thought that an insight into this problem would be had more directly if the recorded reflection wave were simplified in its pattern. This would be true except for the fact that considerable advantage is gained through recording of the second derivative whose amplitude may be many times that of the record of actual ground motion. Enhancement of this property is often employed to advantage through steepening of the wave front of the generated wave which can be accomplished in many instances through a fortuitous choice of shot-hole medium. In these experiments the steepness of the wave front has been varied between limits of .005 and .002 seconds. Wilson has observed the importance of this effect and has predicted the value of a very short period, critically damped, seismograph. He was limited by the sensitivity of the mechanical instrument, a fact which is now of no great importance on account of the amplification available through electrical means.

One particularly undesirable arrangement is presented by an undamped instrument whose period equals that of the ground motion. The response of such a seismograph to this type of excitation yields a series of almost continuous oscillations.

Nearly as serious in its effect upon resolution is the critically damped seismograph whose period is shorter than that of the impulse. This choice consistently adds at least one extra "leg" on the end of the recorded wave, thereby adding to the confusion of the already overworked interpreter.

In all of these experiments damping has been achieved by viscous means, using oil, or by electromagnetic means alone, whereby the degree could be varied over large limits, or by a combination of the two methods. The manner is unimportant.

If the fundamental period and the damping of the reflection wave detector can profoundly affect the appearance of the recorded impulse then it is also true that the time constant and damping of the electrical circuits associated with the detector will have similar effect. In present day electric seismographs it is quite commonly the custom to discriminate against unwanted waves by frequency selecting means. In some instruments preference for reflection impulses is achieved with the use of band-pass filters; in others through the use of high-pass and/or low-pass circuits. Due consideration must be given to the design of filter circuits as well as of associated networks which have potentially resonant characteristics. It is possible to achieve considerable alteration in the shape of recorded impulses by the use of networks of this class. In general their effect is quite similar to that pointed out by Wilson and qualitatively at least his relationships may serve as a guide. These predictions have been verified experimentally by employing electrical networks having a wide range in values of damping and of time constant. The results of these experiments are identical in character to those illustrated for the earth detector shown in Figs. 3 to 5 inclusive.

It has been observed that the surface soil and aerated zone frequently exert some effect on the shape of the reflection wave. Many have pointed out from field work that if the detectors are placed in loose sand, records obtained from the same reflecting horizon cannot be correlated with those obtained when the detectors are placed in moist clay. Studies have been made intending to determine the influence of surface materials and have been reported by Howell, Keen and Thompson.[6] These experiments were conducted with continuous waves and pulses and the writers report that insufficient work was done to achieve results of immediate practical value. Consideration must be given to the effect of this portion of the seismic reflection wave path in establishing control of resolution. Experiments similar to those reported by the writer for stratigraphic analysis[1] are under way and it is hoped that they may be the basis of a future paper on this important subject.

[6] GEOPHYSICS, Vol. V, No. 1, (1940), pp. 1–14.

A NUMERICAL METHOD OF COMPUTING DIP DATA USING WELL-VELOCITY INFORMATION*

KENNETH H. WATERS†

ABSTRACT

A method of computation for calculating steeply dipping strata is presented. It takes full advantage of the velocity information afforded by well shooting and is simple in application. Charts are derived from the velocity data which will give depth and position of the reflecting point together with angle of dip and azimuth of dip immediately from the time and differential time of a reflection taken from a seismic record.

The ability to compute the angle of dip and the position of the reflecting point for a curved-path assumption has long been acknowledged to be almost essential in some regions, more especially in areas where steeply dipping formations are encountered. Numerous attempts have been made and much ingenuity has been displayed in fitting algebraic laws to the change of velocity with depth, or sometimes with time, and, for this initial assumption, in finding the path travelled by a ray. The type of function is limited however since any but the mathematically simplest cannot be integrated at a later stage in the analysis. Unfortunately these simple laws do not fit the well-shooting data very accurately. Mott-Smith[1] has shown that the relations in which the velocity is expressed as a function of the time are more convenient to handle and fit the observed values better than relations giving the velocity as a function of the depth. He also states that more complicated velocity-depth curves "such as the S-shaped ones" have not been investigated. It is the purpose of the present paper to show how all velocity-depth curves may be handled. The only restrictions which will have to be placed on the velocity variations are those which must be fulfilled in order that the variations are physically possible, that is, that there must be a finite number of turning points and no infinities in the region to be examined. The velocity laws which will be studied have one common characteristic. The velocity is the same at any point in a horizontal plane at a given depth. This restriction will, of course, eliminate the computation of dips when the equi-velocity surfaces are anything other than horizontal planes.

* Manuscript received May, 1940.

† National Geophysical Co.

[1] M. Mott-Smith, GEOPHYSICS, Vol. IV No. 1, (1939). p. 8.

It admits, therefore, of no change of velocity at a boundary between two different layers unless this boundary be itself horizontal. If such a boundary is near the surface and is known to be inclined, then its effect may be counteracted by applying a special form of "weathering"

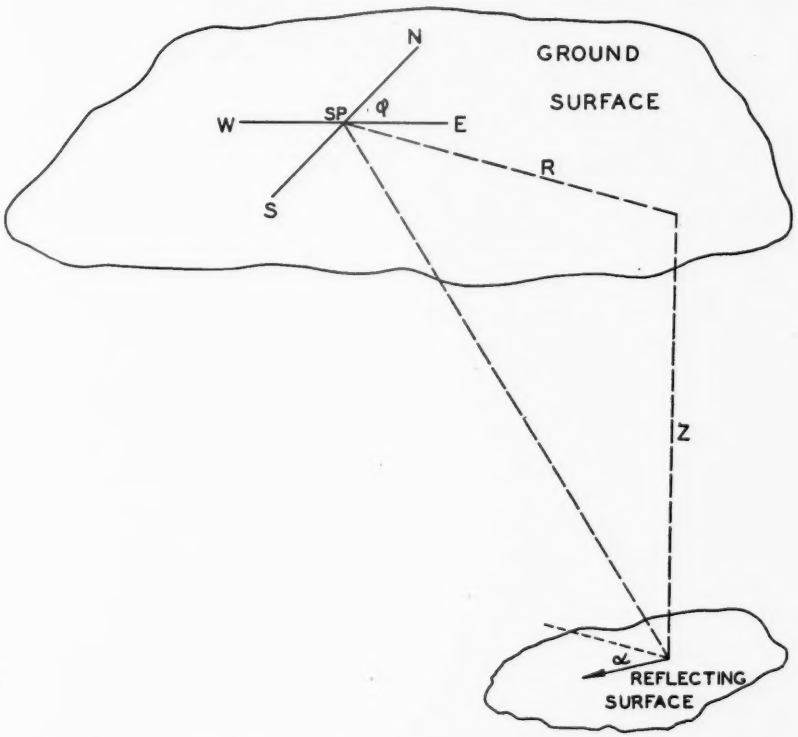

FIG. 1. Diagram showing relationship between shot point and reflecting point and seismometer spreads on the ground surface.

correction. If it is not near the surface, then other measures will be necessary.

Except from an academic viewpoint, it is not necessary to know the path of the ray. All that is necessary in practice is a knowledge of the angle of dip of the horizon from which the reflection comes, and the position of the reflecting point relative to the shot-point. This position is usually given in cylindrical coordinates, the vertical through the shot-point being the cylindrical axis. The azimuth is referred usually

to the north or to some other convenient direction. In order to determine the azimuth two seismometer spreads at right angles are taken (see Fig. 1). Then, since cylindrical symmetry is assumed for the velocity function

$$\tan \phi = \frac{\Delta T_E}{\Delta T_N}$$

where ΔT_E and ΔT_N are the differential times of arrival at opposite ends of the east and north seismometer spreads respectively and ϕ is

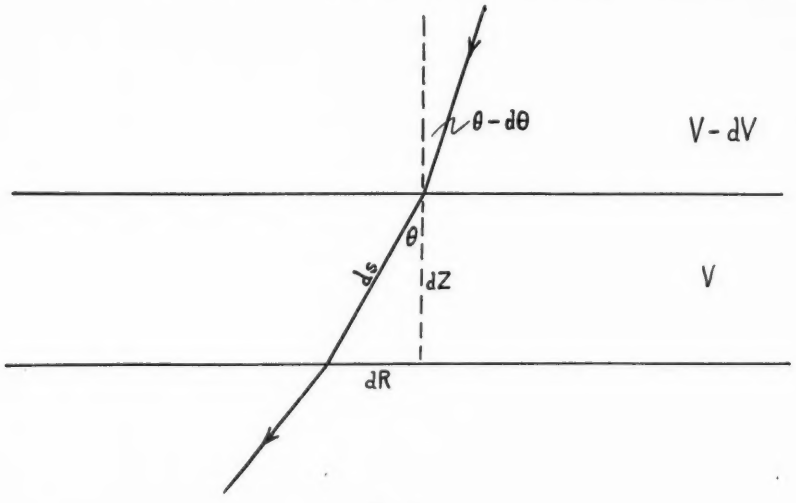

FIG. 2

the azimuth of the dip. It is assumed, of course, that weathering and elevation corrections have already been applied to the differential times.

It now remains to find the vertical depth (Z) and the horizontal displacement (R) of the reflecting point from the shot-point. It is proposed to adopt a numerical method for finding these coordinates. This numerical method will have no disadvantage from the strictly analytical methods in accuracy since both of these rest finally on the accuracy of the original "well shooting" data. The mechanical integrations performed may be made as accurate as necessary by taking a sufficiently large scale for the graphs involved. It will be assumed that the seismic results comprise the total time (T) for the reflection and two differential times ΔT_E and ΔT_N from the two seismic spreads at right

angles. For simplicity, also it will be assumed that these spreads are distributed symmetrically about the shot-point and that one of these spreads lies in a north-south direction.

Some formulae derived in this analysis have been obtained previously by M. M. Slotnick[2] and have been quoted several times by other authors.[3,4] Since, however, the method of derivation is illustrative of the mechanism of this method it will be given briefly below: Consider a thin layer (see Fig. 2) of thickness dz at a depth z below the shot-point. Let the seismic velocity of the layer be V and the velocity immediately above it be $V-dV$. Let a ray strike the upper surface of the layer, making $\theta-d\theta$ with the vertical. Then, by Snell's law, if refraction takes place

$$\frac{\sin\theta}{\sin(\theta - d\theta)} = \frac{V}{V - dV},$$

or

$$\cos\theta d\theta = dV.$$

If this elementary equation be integrated it may be found that

$$\frac{\sin\theta}{\sin\theta_0} = \frac{V_z}{V_0}, \tag{1}$$

where θ is the angle to the vertical at a depth z and θ_0 is the angle at the surface, V_0 the velocity at the surface, V_z is the velocity at any depth z.

In particular it should be noted that

$$\frac{\sin\alpha}{\sin\theta_0} = \frac{V_R}{V_0} \tag{2}$$

where α is the angle of dip, V_R is the velocity at the reflecting point. It may be proved by purely geometrical considerations that the differential times from records taken on two spreads at right angles may be compounded to give the corresponding differential time along with the direction of maximum dip according to the formula

$$\Delta T = [(\Delta T_E)^2 + (\Delta T_N)^2]^{1/2}. \tag{3}$$

[2] M. M. Slotnick, GEOPHYSICS, Vol. 1 No. 1, (1936), p. 9.
[3] C. E. Houston, GEOPHYSICS, Vol. 4 No. 4, (1939), p. 242.
[4] C. H. DIX, GEOPHYSICS, Vol. 4, No. 1 (1939), p. 81.

If X is the effective length of the seismometer spread used it is evident that

$$\frac{V_0 \Delta T}{X} = \sin \theta_0, \tag{4}$$

and hence, utilizing the relation (1) above

$$\frac{V_z \Delta T}{X} = \sin \theta. \tag{5}$$

The total time for the energy to travel from the shot-point to the reflecting point and back to the seismometer spread is given by

$$T = 2 \int_0^z \frac{ds}{V_z}, \tag{6}$$

where ds is an element of path.

$$T = 2 \int_0^z \frac{dz}{V_z \cos \theta} = 2 \int_0^z \frac{dz}{V_z (1 - \sin^2 \theta)^{1/2}}$$

$$= 2 \int_0^z \frac{dz}{V_z^2 \left[\frac{1}{V_z^2} - \left(\frac{\Delta T}{X} \right)^2 \right]^{1/2}}. \tag{7}$$

introducing the symbol V_H to represent the phase velocity along the ground surface ($= X/\Delta T$) this formula may be written

$$T = 2 \int_0^z \frac{dz}{V_z^2 \left(\frac{1}{V_z^2} - \frac{1}{V_H^2} \right)^{1/2}} = 2 \int_0^z F_1 dz. \tag{8}$$

In this way the important relationship is brought out that no reflection will be received if its phase velocity along the ground surface is less than the velocity at the reflecting bed. For convenience the integrand of this integral will be denoted by F_1.

In a very similar way the horizontal displacement (R) may be obtained.

$$R = \int_0^z \tan \theta dz$$

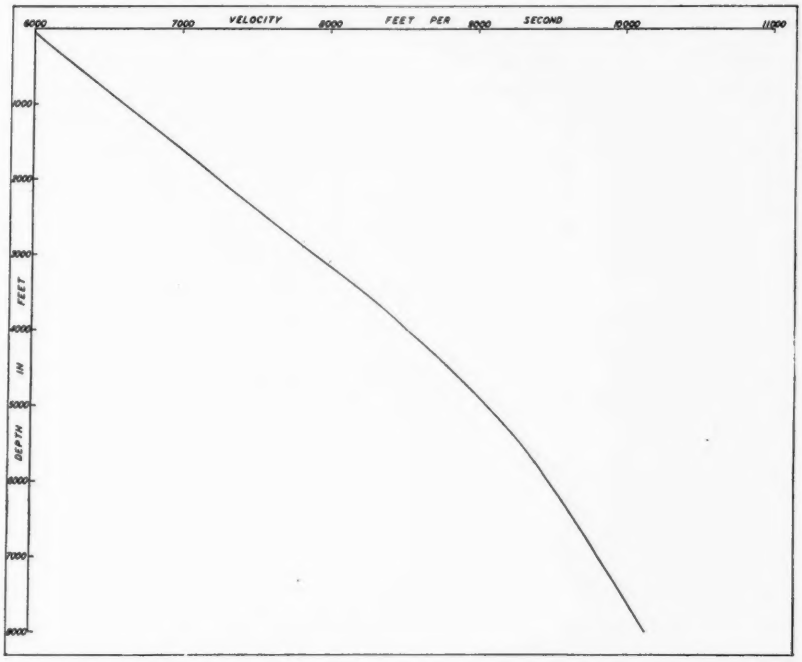

FIG. 3. Interval velocity curve on which sample work is based.

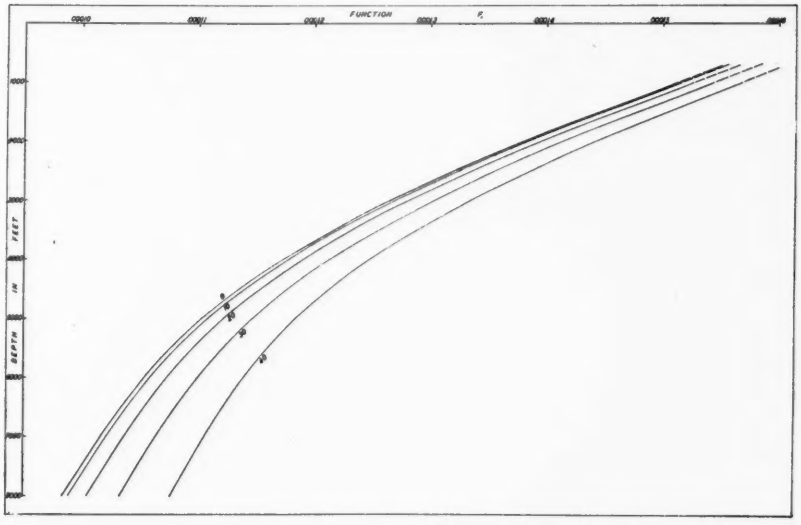

FIG. 4. Curves showing the relationship between F_1 and $_2$ for various values of $\Delta T/X$. Values of $\Delta T/X$ marked on the curves are in units of 10^{-6}.

$$= \int_0^z \frac{\sin\theta}{(1 - \sin^2\theta)^{1/2}}\, dz$$

$$= \int_0^z \frac{\sin\alpha}{V_R} \cdot \frac{V_z}{\left[1 - \frac{\sin^2\alpha}{V_R{}^2}\,(V_z{}^2)\right]^{1/2}}\, dz$$

$$= \int \frac{\Delta T}{X} \cdot \frac{1}{\left(\frac{1}{V_z{}^2} - \frac{1}{V_H{}^2}\right)^{1/2}}\, dz = \int_0^z F_2 dz. \qquad (9)$$

The integrand of this integral will be denoted by F_2. Suppose now that ΔT is known from the records, the function F_1 can be calculated for

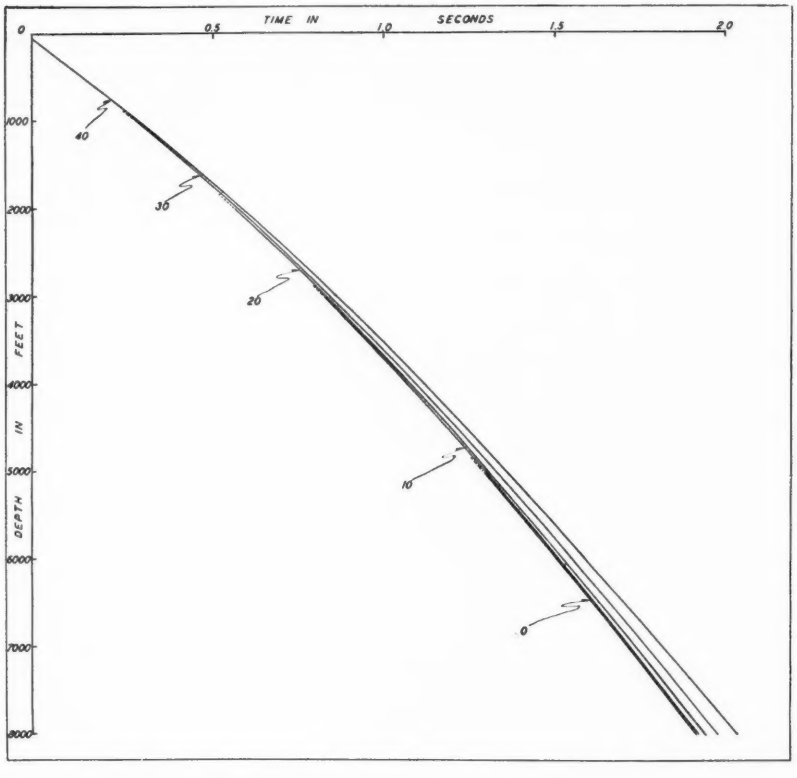

FIG. 5. Curves showing relationship between T and z. $\Delta T/X$ values on curves are given in units of 10^{-6}.

any depth since the interval velocity (V_z) is obtainable immediately from Fig. 3. A set of curves may thus be drawn showing the relation between z and F_1. A sample set of such curves for various values of $\Delta T/X$ are given in Fig. 4.

The area between any curve in Fig. 4 from the z axis to the curve from the line $z=0$ to any depth will then give half the total time for the wave path to a reflecting point having that depth and the angle of dip specified. Thus for any given differential time a curve may be drawn showing the relation between T and z. The time, however, is known directly from the record as is also the differential time and this latter curve will therefore give a direct method of finding Z. Sample curves, calculated from the interval velocity curve (Fig. 3) are given in Fig. 5. The procedure in finding the depth (Z) is simple. The differential time appearing on the record is taken, $\Delta T/X$ calculated, the corresponding curve in Fig. 5 selected, and from the value of T on the record, the corresponding depth is obtained.

By plotting a set of curves showing the relation between F_2 and

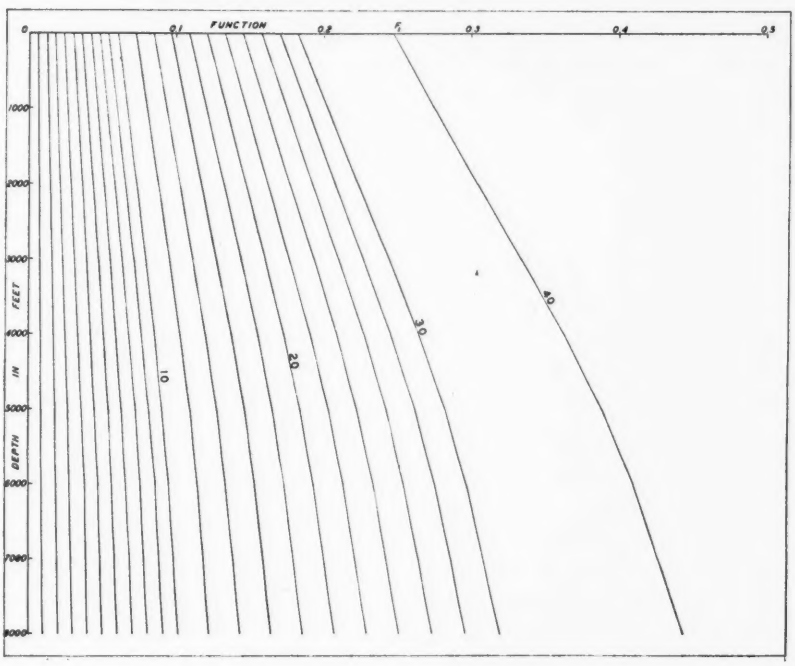

FIG. 6. Set of curves for various values of $\Delta T/X$ showing relation between F_2 and z. $\Delta T/X$ values are in units of 10^{-6}.

z and integrating these mechanically in precisely the same way that the integration of the F_1 curves were effected, the relations between R and z for various values of the differential times are obtained (see Figs. 6 and 7). The value of Z has already been obtained from Fig. 5 and by selecting the proper curve (with the correct value of $\Delta T/X$) the value of R is obtained.

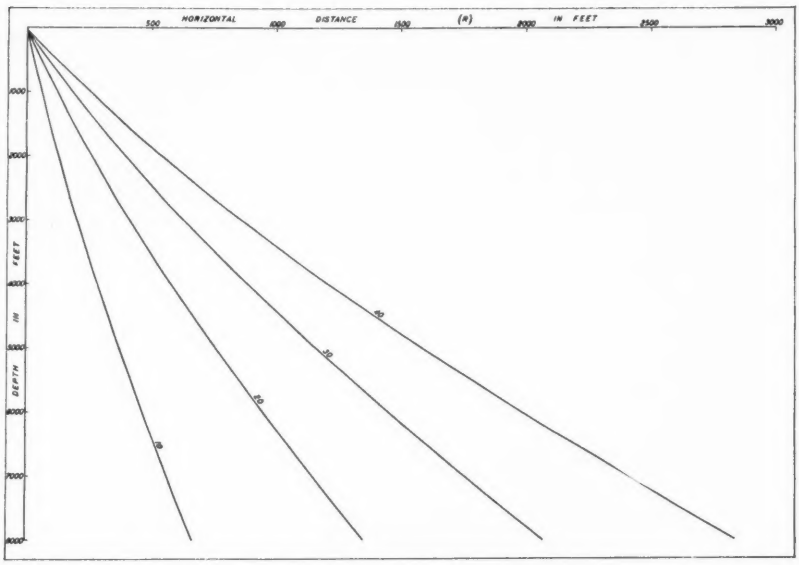

FIG. 7. Curves showing variation of R with z for various values of $\Delta T/X$. $\Delta T/X$ is marked on curves in units of 10^{-6}.

The last stage in the calculation is the determination of the angle of dip. Fig. 3 shows the variation of the interval velocity with the depth as determined by "well shooting." Since Z is already known it is a simple enough matter to determine V_z from this curve and thence to obtain the angle of dip from the formula

$$\sin \alpha = V_R \cdot \frac{\Delta T}{x} \cdot \tag{10}$$

Although the method sketched above will doubtless leave very much to be desired from the point of view of mathematical completeness, especially with regard to the actual path taken by the seismic waves, it nevertheless presents one solution of the problem of utilizing

the knowledge obtained from shooting a well in the determination of dips when the strata are dipping steeply. Hitherto such knowledge could be applied only if, without much error, the beds were dipping so slightly that they could be assumed flat. The advantage of the method proposed is that any velocity-depth law may be utilized no matter how far it may depart from simple mathematical formulation. The method is simple and, once the necessary curves are obtained, is quick in application. The most obvious disadvantage is the amount of labor involved in computing the values used in drawing the curves. This, however, is largely offset by the fact that it is necessary to make these laborious calculations only once for each well shooting, and the curves obtained may be used in hundreds of dip determinations.

A TRANSFORMED WAVE-FRONT CHART*

RAYMOND A. PETERSON†

ABSTRACT

In seismograph computations assuming a uniform rate of velocity increase with depth, a "wave front-wave path" chart consisting of sets of orthogonal circles is often used. The present paper describes a transformation by which the wave fronts become a set of concentric circles with the wave paths as radii, while the cartesian coordinates representing vertical and horizontal distances in the ground become orthogonal circles.

As an initial approximation in reflection seismograph computations, the velocity of wave propagation in the ground is often assumed to increase at a uniform rate with depth. That is, if v denotes the velocity at depth y below the shot origin, then:

$$v = v_0 + ay. \tag{1}$$

The equations of the wave fronts and wave paths for this case have been derived in papers by Ewing and Leet[1] and by M. M. Slotnick.[2,3] A wave generated at the shotpoint travels outwards in the form of an expanding sphere (Fig. 1) which drifts downwards as the radius increases. At any time t after the shot instant, the radius of the wave front is given by:

$$R = K(\sinh at), \tag{2}$$

where

$$K = v_0/a,$$

and the depth of the center below the shot origin by:

$$H = K(\cosh at - 1). \tag{3}$$

Likewise, the wave paths are circles passing through the shot origin, with their centers on the plane:

* Presented at the Annual Meeting, Chicago, Ill., April 9, 1940.

† United Geophysical Co., Pasadena, California.

[1]. Maurice Ewing and L. Don Leet, "Seismic Propagation Paths." Transactions of the A.I.M.E., *Geophysical Prospecting*, 1932. pp. 245–262.

[2] M. M. Slotnick, "On Seismic Computations, with Applications, I." GEOPHYSICS, Vol. 1, No. 1. (1936). pp. 9–22.

[3] M. M. Slotnick, "On Seismic Computations, with Applications, II." GEOPHYSICS, Vol. 1, No. 3. (1936). pp. 299–305.

$$y = \frac{1}{a} - K,$$

and with radii:

$$Q = K \csc \theta_0, \tag{4}$$

where

θ_0 = angle of emergence of the wave path, Fig. 1.

The angle θ between the wave path and the vertical at travel time t is given by the relation:

$$\tan \theta/2 = (\tan \theta_0/2) \cdot e^{at}. \tag{5}$$

If a wave front impinges normally at point P (Fig. 1) on a reflecting interface dipping with angle θ, the path of the reflected wave will

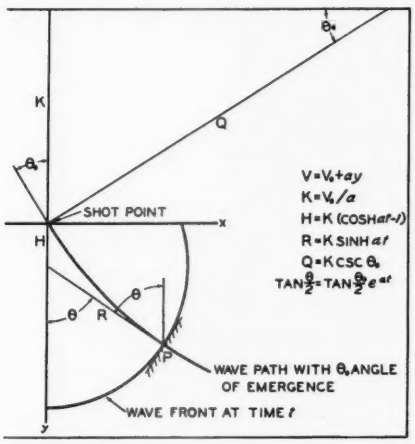

FIG. 1

coincide with the path of the incident wave. If the arrival time, T_r, of the reflected wave is measured on a surface geophone-spread symmetrical about the shotpoint and oriented in the direction of dip of the reflecting interface, the angle of emergence, θ_0, can be calculated from the relation:

$$\sin \theta_0 = v_0(dT_r/dx) \tag{6}$$

where

x = the horizontal coordinate along the spread.

The dip, θ, can then be calculated from equation (5).

For computing the position of the reflecting interface it is convenient to construct a "wave front-wave path" chart showing the position of the wave front for progressive intervals of time, and of the wave paths for various values of θ_0 (Fig. 2). In the present case the chart will appear as two orthogonal sets of circles superimposed on cartesian coordinates representing vertical and horizontal distances in the ground. If the wave front circles are graduated in terms of reflection time at the shotpoint, and the wave paths in terms of sin θ_0, the position of the reflecting interface can be read directly by finding the intersection of the proper coordinates on the chart.

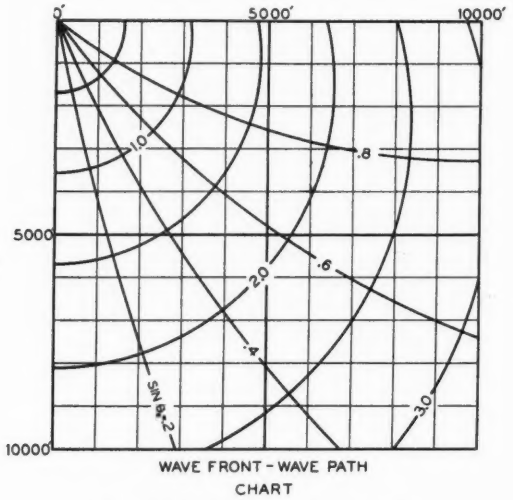

FIG. 2. Wave front-wave path chart.

Fig. 2 shows schematically only a few of the lines necessary for accurate interpolation. In an actual chart with four superimposed sets of closely spaced coordinates, repeated reading of data is a tiring process. The purpose of this paper is to describe a transformation by which the wave fronts become circles concentric about the shotpoint, and the wave paths become radii through the origin. The wave fronts and wave paths can then be replaced on the chart by a mechanical arm pivoted at the shot origin, and graduated with a scale showing the wave front position for progressive intervals of time (Fig. 3). The sine of the angle of emergence, sin θ_0, may be read directly on a circular scale at the lower end of the pivoted arm. In the process of the trans-

formation, the cartesian coordinates are warped into orthogonal sets of circles (Fig. 3). The transformed chart is used in the same fashion as the original chart, except that the reflection time and sin θ_0 are read on the appropriate scales.

The equation of the wave front circles may be written:

$$x^2 + (y - H)^2 = R^2,$$

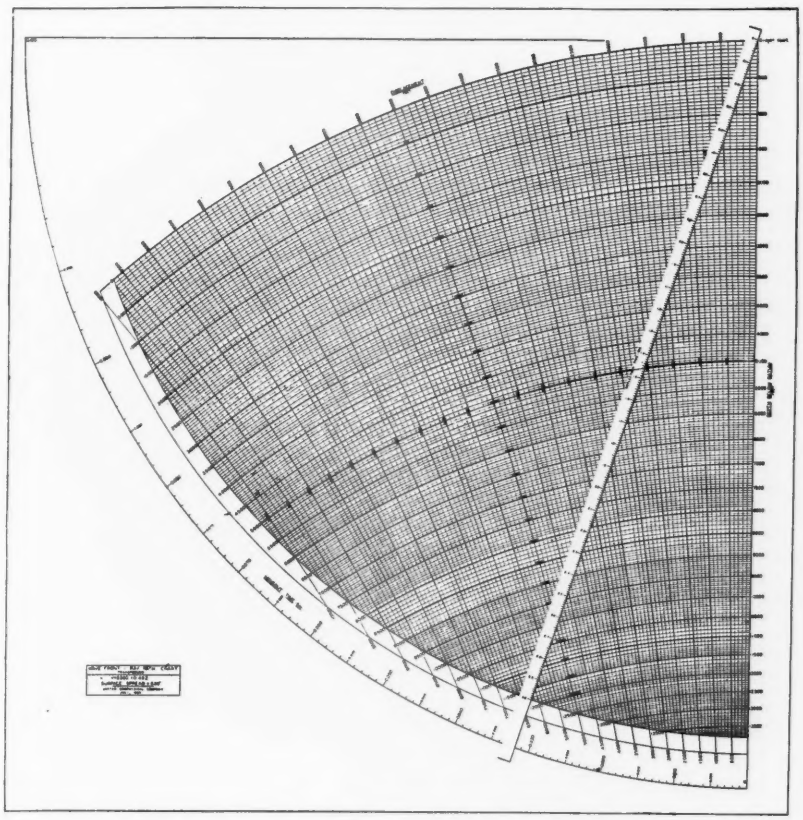

FIG. 3. Transformed wave front-wave path chart.

or

$$x^2 + [y - K(\cosh at - 1)]^2 = K^2 \sinh^2 at. \tag{7}$$

The equation of the wave path circles may be written:

$$(x - Q \cos \theta_0)^2 + (y + K)^2 = Q^2,$$

or

$$(x - K \cot \theta_0)^2 + (y + K)^2 = K^2 \csc^2 \theta_0. \tag{8}$$

If the substitutions:

$$\begin{aligned} \sinh at &= \operatorname{csch} U, \\ \cosh at &= \coth U, \\ \theta_0 &= V, \end{aligned} \tag{9}$$

are made, equations (7) and (8) become:

$$x^2 + [y - K(\coth U - 1)]^2 = K^2 \operatorname{csch}^2 U, \tag{10}$$

$$(x - K \cot V)^2 + (y + K)^2 = K^2 \csc^2 V. \tag{11}$$

Now equations (10) and (11) are identical in form with those for the equipotential surfaces and lines of force in the electrostatic field between two charged, parallel, circular cylinders.[4] Accordingly, the methods of conformal transformation commonly used in potential theory can be applied to the wave front chart.

Let the original chart be represented in the z plane, where:

$$\begin{aligned} z &= x + jy \\ j &= \sqrt{-1} \end{aligned} \tag{12}$$

and the transformed chart be represented in the ζ plane, where:

$$\zeta = \xi + j\eta. \tag{13}$$

It can readily be shown[4] that the quantities U and V defined by equations (10) and (11) may be represented by the real and imaginary parts of the function:

$$\begin{aligned} W &= U + jV \\ &= \ln (z + 2jK)/z. \end{aligned} \tag{14}$$

To accomplish the desired transformation of the wave front chart, let

$$W = \ln \frac{jK}{\zeta}. \tag{15}$$

Separating (15) into its real and imaginary parts, and eliminating U and V, there results:

[4] William R. Smythe, "Static and Dynamic Electricity." McGraw-Hill, 1939. pp. 74–76.

$$\xi^2 + \eta^2 = K^2[(\cosh at - 1)/\sinh at]^2 \tag{16}$$

and

$$\xi/\eta = \tan \theta_0. \tag{17}$$

Equation (16) demonstrates that the transformed wave fronts are circles concentric about the shotpoint, (Fig. 4), with radii equal to:

$$K(\cosh at - 1)/\sinh at = K(H/R). \tag{18}$$

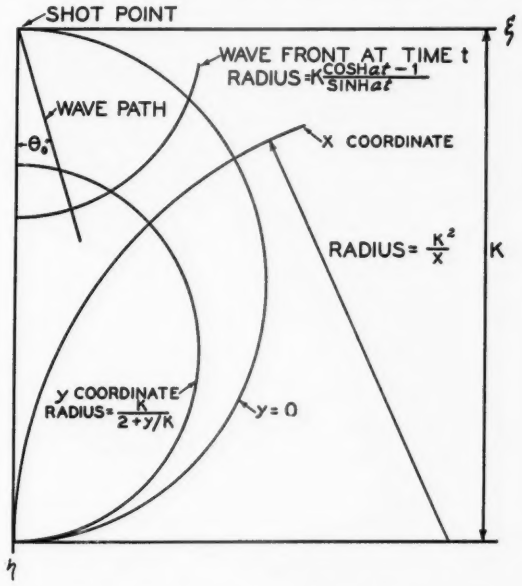

FIG. 4. Transformed wave front chart.

The wave paths as indicated by equation (17) are radii through the shotpoint, making an angle θ_0 with the vertical.

The equations of the transformed cartesian grid in the ζ plane may be obtained by equating (14) and (15). Then:

$$\zeta = jKz/(z + 2jK) \tag{19}$$

or

$$z = 2jK\zeta/(jK - \zeta). \tag{20}$$

Separating the real and imaginary terms in (20) and regrouping terms, there results:

$$\xi^2 + \left(\eta - \frac{K^2 + Ky}{2K + y}\right)^2 = \left(\frac{K^2}{2K + y}\right)^2 \tag{21}$$

and

$$(\xi - K^2/x)^2 + (\eta - K)^2 = (K^2/x)^2. \tag{22}$$

From (21) it follows that the transformed y coordinates are circles having their centers on a vertical line through the shot origin, and a common point of tangency at a distance K below the origin. The radii of the circles are equal to

$$K/(2 + y/K).$$

Likewise, from (22) it follows that the transformed x coordinates are circles having their centers on a horizontal line at a distance K below the shot origin, and a common point of tangency vertically below the origin. The radii of these circles are:

$$K^2/x.$$

From the above data, a transformed wave front chart can be constructed for any particular values of v_0 and a. If desired, the chart may be calibrated in terms of dimensionless parameters.*

* M. M. Slotnick has pointed out that the transformation described in this article can be accomplished by the method of inversion.

DISCUSSIONS AND COMMUNICATIONS

TIDAL GRAVITY OBSERVATIONS

Last August I sent you the manuscript of a paper on tidal gravity variations. Since that time, we made another test run of the gravimeter with very similar results. I am sending you a chart of the curves of gravity variation which we obtained.

Curve A in the chart shows instrument readings converted into milligals, at twenty-minute intervals.

Curve B is the gravimeter drift curve, obtained by plotting twenty-four hour running averages of instrument readings.

The observed tidal gravity variation is shown by curve C, obtained by subtracting the drift from observed instrument readings.

The broken line, curve D, represents the theoretical tidal gravity variation for an unyielding Earth.

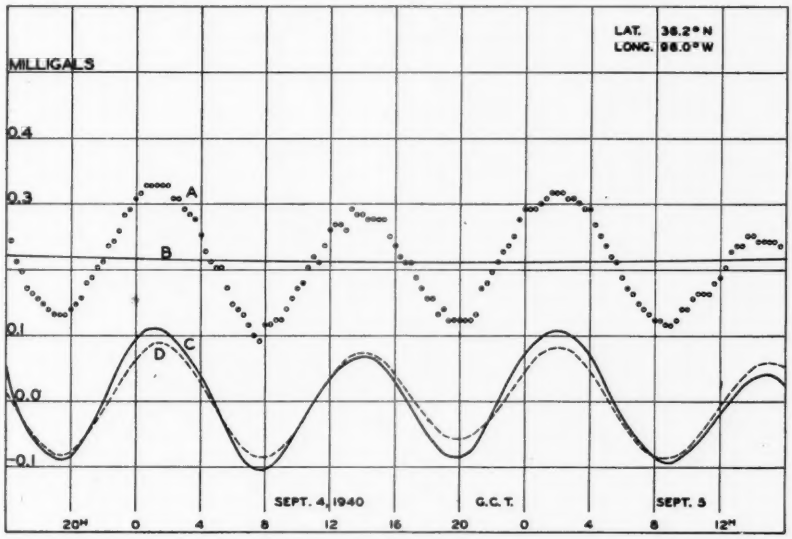

FIG. 1a. Tidal gravity variation
A—Gravity meter readings
B—Drift curve
C—Observed gravity variation
D—Theoretical gravity variation

I computed the value of the factor $1+h-3k/2$ by comparing the maximum variation of gravity for successive cycles of the observed and of the theoretical curves, C and D. The average value obtained in this way is 1.2, the individual factors range from 1.1 to 1.4. This average value is the same as that obtained by a similar procedure from observations made in December, 1939.

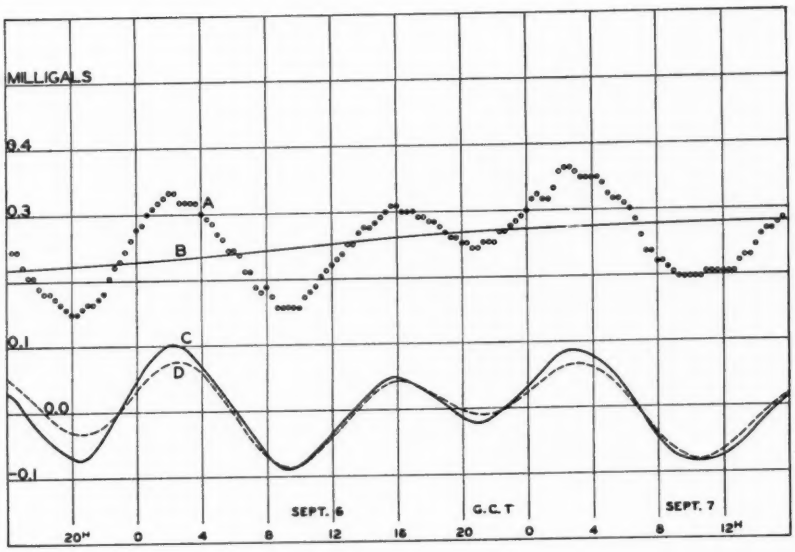

FIG. 1b. Tidal gravity variation.

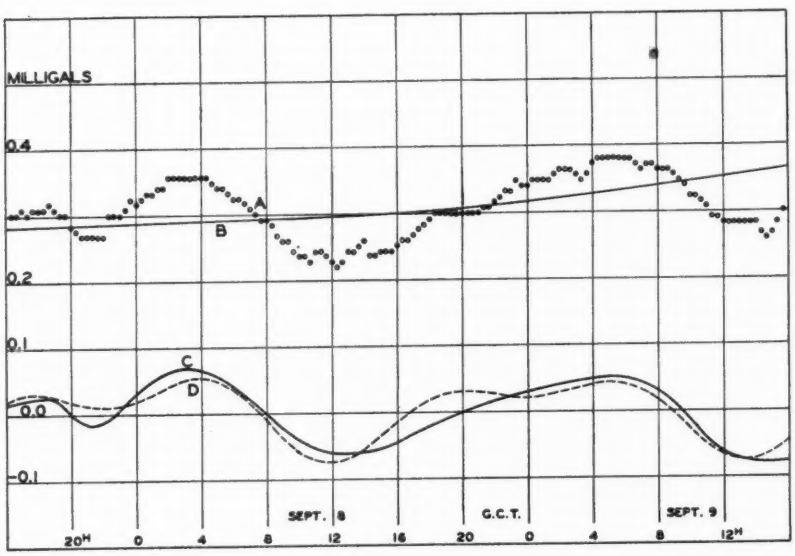

FIG. 1c. Tidal gravity variation.

An interesting fact was brought out in regard to the drift of the gravimeter. The first part of the observations, up to September 5, 20^h G.C.T., was taken without clamping the gravimeter between the readings. Between that time—September 5, 20^h—and the end of the run the gravimeter was clamped after a reading was taken and unclamped just before the next reading. An examination of curve B shows that the drift of the instrument was very small, less than the probable error of a reading, as long as the instrument was left unclamped. The drift of the gravimeter in the second part of the record—from September 5, 20^h G.C.T. up to the end of the record—when the instrument was clamped between readings, was very much greater and of the same order of magnitude as during the run made in December, 1939.

October 4, 1940

A. WOLF
Geophysical Research Corp.

A.I.M.M.E.—ANNUAL MEETING, NEW YORK

PROGRAM OF THE COMMITTEE ON GEOPHYSICS COURSES

Monday afternoon, February 17th, 1941

ORGANIZATIONS PARTICIPATING IN THE MEETING

Committee on Geophysics Courses, M.I.E.D., A.I.M.E.
Committee on Geology Courses, M.I.E.D., A.I.M.E.
Committee on Geophysics, A.I.M.E.
Committee on Mining Geology, A.I.M.E.
Society of Economic Geologists
American Geophysical Union
Committee on Applications of Geology, A.A.P.G.

PRESIDING OFFICERS

Quentin D. Singewald, Chairman Program Committee, Society of Economic Geologists,
and
Sherwin F. Kelly, Chairman, Geophysics Courses Committee.

PAPERS

The Education of the Exploration Geophysicists and the Geologist, by M. M. Slotnick Exploration Dept. Humble Oil & Refining Co. (10 mins)

"The Nature of Geological Inquiry and the Training Needed for it," by W. H. Bucher, Professor of Geology, Columbia Univ. (20 mins)

The Influence of Geophysics and Geochemistry on the Professional Training of Geologists, by W. C. Krumbein, Asst. Prof. of Geol. Univ. of Chicago. (35 mins)

The Content of Geological Engineering Courses, by H. W. Straley, III, Professor of Geology, Baylor University, Waco, Texas. (10 mins)

The Place of Observational Geology, Past and Present, by Benjamin Miller, Prof. of Geology, Lehigh Univ. Bethlehem, Pa. (30 mins)

Essentials in Modern Geological Education, by Richard M. Field, Pres. American Geophysical Union. (15 mins)

Aspects other than Technical of Student Training, by Sherwin F. Kelly, Pres. Geophysical Explorations Ltd. and Sherwin F. Kelly Geophysical Services, Inc. (10 mins)

Tuesday morning, February 18th, 1941

ORGANIZATIONS PARTICIPATING IN THE MEETING

Committee on Geophysics Courses, M.I.E.D., A.I.M.E.
Committee on Geophysics, A.I.M.E.
American Geophysical Union

PRESIDING OFFICERS

Richard M. Field, President, American Geophysical Union
and
W. R. Chedsey, Chairman, M.I.E.D., A.I.M.E.

PAPERS

A College's Contribution to a Geophysicist's Training, by L. Don Leet, Seismologist, Harvard Univ. (20 mins)
An Arts and Science Curriculum in Geophysics, by James Macelwane, S.J. Dir. Dept. of Geophysics, St. Louis University. (10 mins)
Committee Report (40 mins)
A Geophysics Option in a Comprehensive Earth Science Curriculum, by Helmut Landsberg, Asst. Prof. of Geophysics, Pennsylvania State College. (15 mins)
(Title later), by David T. Griggs, Dept. of Geology, Harvard Univ.; Secy. Section of Tectonophysics, American Geophysical Union. (30 mins)

REVIEWS

Exploration Geophysics, by J. J. Jakosky. Times Mirror Press, Los Angeles, Cal., 1940. 786 pp. $8.00

The author of this book has a substantial background of practical as well as some teaching experience in his subject. He is well known as a contributor to various geophysical subjects, but especially to the art of electrical prospecting and his treatment of this branch of exploration is exceptionally well done. The chapters devoted to it are outstandingly the best in the book. The chapter on Gravitational Methods is the weakest.

The entire book has a distinctly practical flavor. Jakosky is evidently interested in theories and principles primarily because they have actual or potential application in the business of prospecting.

The first two chapters are written primarily for those who deal with geophysical methods administratively, it being assumed that they may do some reading on the subject. These chapters deal with the nature and application of various methods to petroleum geology and mining, and to various engineering problems, including those of water supply and storage, civil and highway engineering.

There follow five chapters which deal with the four geophysical methods, the use of which has led to important discoveries of minerals. Two of these chapters deal with electrical methods and the others with the magnetic, gravitational and seismic techniques. These chapters present the underlying physical principles, the properties of the rocks which are involved and the various techniques which are available for application to the practical solution of geophysical problems. The instruments which have been developed and the problems of actual field operations are given due consideration. Results of actual surveys are presented and their interpretation is discussed.

Literature references are given as footnotes. They are hardly sufficient to provide ready access to much of the pertinent available literature. A useful feature is the list of United States, British, Canadian, French, German and Russian patents given at the end of each chapter. The value of these lists is somewhat impaired by the fact that some patent references are given as footnotes in the body of the text and these apparently have not been included in the list at the end of the chapter. The repetition of these patent references to make the lists complete would have greatly enhanced their value.

The remaining chapters of the book deal with geo-chemical and geo-thermal methods, drill hole investigations, physical principles applied to production problems and with permit and trespass practice and insurance. The presence of the chapter on production problems in a treatise on exploration is somewhat surprising, but the echo method for determining the depth to the fluid level in wells is essentially a geophysical technique and the application has been developed by geophysical operators, Jakosky being one of them.

The book reads easily because the author has the facility for presenting ideas clearly. There are occasional exceptions to this as for example, the description of the Hoyt gravimeter (p. 174). Jakosky's *Exploration Geophysics* offers a satisfactory summary of this important art brought down to date. It will be of interest to readers professionally engaged in this art, and it should be well received by the profession.

E. A. ECKHARDT

Geophysical Exploration, by C. A. Heiland. Prentice-Hall, Inc., New York, 1940. 1013 pp. $10.00.

Professor Heiland enjoys the distinction of heading the oldest department of applied geophysics in an educational institution in the United States. He has also dealt with the subject as a consultant and as a geophysical contractor. The author's preoccupation with geophysics as an educational subject is strongly reflected in the pages of *Geophysical Exploration*. The book is encyclopaedic and academic in character. This is by no means to say that the practical aspects of the subject are neglected. The subject is comprehensively treated, in some cases exhaustively so. The discussion of the Eötvös torsion balance and directly related material is very complete and excellent, but the amount of space devoted to an instrument and related techniques which are practically obsolete violates the reviewer's sense of proportion. The treatment of magnetic instruments available for prospecting is excellent.

The book is divided into two parts. The first part of 62 pages explains the nature and uses of the methods covered in greater detail in the second part of the book. In this part there are no equations. It is intended for readers who may be interested in knowing what the geophysical methods are and how and why they may be used. Brief chapters discuss the application of these methods to oil exploration, mining and engineering. In part two the four major methods of geophysical prospecting, gravitational, magnetic, seismic and electric are discussed in detail in as many chapters. At the beginning of each chapter one finds a definition of the symbols used, followed by a suitable discussion of pertinent physical theory. The physical properties of the rocks which are involved are discussed and laboratory and field methods for their determination. Excellent tables give values for many rocks of interest to the practical geophysicist. The special techniques of the method are discussed and the instruments available for their application are reviewed, In most cases illustrative examples of actual surveys are given, but in the chapter on Seismic Methods, this illustrative material is very meager.

The two final chapters cover Geophysical Well Testing and Miscellaneous Geophysical Methods.

The reviewer is compelled to challenge the statement on page 19 that magnetic anomalies of over 50 gammas may be assumed to arise from variation in elevation or composition of the underlying igneous rocks and that anomalies of less magnitude are usually due to similar variations in the sedimentary rocks. On page 425 it is stated that the structure at Oklahoma City corresponds to a negative magnetic anomaly. Measurements made by reviewer's company in 1928 after only the discovery well had been drilled show an orthodox magnetic high.

Literature references are given as footnotes throughout the text and are reasonably adequate. The absence of any reference to a number of important papers which readily come to mind detracts from the value of the book in affording easy access to the pertinent literature in any field. Reference to patents seems to have been studiously avoided and the few that have been mentioned are found in the body of the text where they would be hard to find if such references are sought.

Dr. Heiland's book is easily the most comprehensive one on the subject of exploration geophysics now available. It should find favor with all who are actively interested in its subject.

E. A. ECKHARDT

Geophysical Prospecting for Oil, by L. L. Nettleton. McGraw-Hill, 1940. 650 pp., $5.00.

In his preface, Dr. Nettleton states that his book is an outgrowth of a course of lectures given for several years at the University of Pittsburgh, and that the work is intended for the student and lay reader rather than for the geophysical specialist. The volume is nevertheless of considerable interest to the practicing geophysicist and will form a worth-while addition to his library. There has been a real need for a concise but comprehensive treatment of the principles of the various geophysical methods and their application to prospecting for oil. By using a direct approach to his material and avoiding verbiage, Dr. Nettleton has succeeded in meeting this need in a very satisfactory manner.

The book is divided into four sections. One of 146 pages, deals with Gravitational Methods, another, of 74 pages, with Magnetic Methods. The Seismic Methods are discussed in a section of 132 pages and the final section of 156 pages discusses Electrical and Miscellaneous Methods, together with measurements of various types commonly made in drill holes. A brief and sensible discussion of the interpretation of geophysical data forms a concluding chapter. The presentation of material in each section follows a logical system, beginning in each case with a discussion of the fundamental principles involved, and the relationship of the quantities measured to geological structure. The instruments used are then briefly described, and the field techniques employed are discussed in some detail. The method of reducing observations is then outlined and usable systems of computation pertinent to the method are presented. Finally, the interpretation of the results obtained is discussed. Appended to each section is a well selected bibliography which, while not exhaustive, is a practical one for reference purposes.

The section on Gravitational Methods is particularly good. The theory of the Eötvös balance is given and the precision pendulum is briefly discussed, but the author has very properly emphasized the present day importance of the gravimeter. The discussion of this instrument and its use leaves little to be desired even by the practicing geophysicist.

The section on Magnetic Methods points out the similarity of all potential field methods and so ties in very nicely with the preceding discussion of gravitational methods. At the same time the differences between magnetic and gravitational effects are pointed out to explain the limited usefulness of magnetic methods.

The section on Seismic Methods is well adapted to the needs of the student, but is of less interest to the geophysicist practicing in that field. The professional geophysicist may object to some of the author's statements, even though recognizing that they are made in the interest of simplification. For example, the discussion of weathering corrections, and the weathering computation schemes presented in connection therewith, leave the reader with the rather definite impression that the so-called weathered layer is, in fact, a discrete surface layer of low velocity. Similarly, in a very brief mention of the application of curved-path wave theory to reflection shooting, the statement is made that the assumption of linear paths will rarely result in errors in the computation of depth to a reflecting layer; but no mention is made of the possible errors which may be introduced into the computations of steep dips. On the other hand, the treatment of the subject is quite complete in that it outlines usable field techniques and definite systems of computation. After perusing the chapter the student will have a very definite idea of "how it is done" although he can hardly expect to be able to do it.

The final section of the book is rather sketchy because of the large number of

topics covered. Electrical prospecting methods are treated briefly but in sufficient detail to explain their relative unimportance in the search for oil. A chapter is devoted to a discussion of resistivity and natural potential surveys in oil wells. The failure to include here a reproduction of a typical electrical log is rather startling since the book, in general, is extremely well illustrated. Geochemical methods are mentioned only in passing as "not proven." Mention is made also of various methods used in wells such as core orientation, determination of fluid levels, and radioactivity logs.

The author's final chapter on Geophysical Interpretation will be interesting reading for all geophysicists since it includes a very sane view of the problems arising when physics meets geology.

Dr. Nettleton's book should be an excellent text for use either in a course designed for undergraduate physicists who intend to specialize in geophysics or in a course designed for geologists and petroleum engineers who wish to obtain an understanding of the various geophysical methods. As a textbook it has the very definite advantage of having been written by a practicing geophysicist, and from the physical point of view. The author has not hesitated to use mathematical treatment wherever necessary, but the physical background for the mathematical expressions is always emphasized. From the mathematician's point of view such treatment is not elegant, but it is much to this reviewer's liking.

This book is particularly recommended to all technical men recently employed in geophysical work. It should also prove useful to geologists associated with geophysical surveys.

To summarize: This is a good book, well written, and well illustrated.

W. T. Born

SUMMARY

It is noteworthy fact that three very excellent books dealing with geophysical prospecting should appear in the United States almost simultaneously. A great deal of literature in the field of applied geophysics has been accumulating scattered through the physical, geological, mining and geophysical journals and the books which have been available up to now really belong to an earlier era of this rapidly advancing art. All three authors have substantial practical experience in geophysical prospecting. All of them have taught the subject to college students and all of them have made contributions to its technical literature. Nettleton's book, reviewed here by Dr. Born, restricts itself to prospecting for oil and is, if that restriction is acceptable, the best introductory text on the subject now available. At the same time the book is at least equally interesting to the specialist, especially his treatment of the gravity method of prospecting, of which he is an outstanding practitioner.

As is perhaps to be expected, all the books strongly reflect the known special interests of their respective authors. This is perhaps best illustrated by the following table which illustrates the proportions of space allocated to major subjects:

	Magnetic	*Gravity*	*Seismic*	*Electrical**
Jakosky	12.2%	12.7%	24.9%	24.7%
Heiland	14.2%	23.3%	18.1%	20.4%
Nettleton	16.9%	32.7%	30.0%	5.0%

* Exclusive of well logging.

The seismic method is at present, has been and at least so long as oil is the pre-

dominant objective of geophysical prospecting, is likely to be the most widely practiced of geophysical methods. If degree of utility is the criterion for space allocation, the seismic method undoubtedly deserves first place. As a matter of history, the gravity method unquestionably ranks second on the same basis. Nettleton's 5% of space to electrical prospecting (exclusive of well logging) is more in line with the limited aggregate of such work done in prospecting for oil. Jakosky's and Heiland's substantially greater space allocation recognizes the great volume of published literature and of patents on electrical prospecting.

It seems unfortunate that the titles of Jakosky's and Heiland's books are not interchanged because, although the difference is not very great, Jakosky's subject seems to the reviewer to be geophysical exploration and Heiland's, exploration geophysics. In each book a geophysicist may expect to find things he may want and which he will not find in the others and probably he can not afford to leave any one of them off his bookshelf.

E. A. ECKHARDT

Lecture Notes on Practical Petroleum Geophysics, by Garrett Kemp.

This small booklet contains lecture notes from a "Conference on Practical Petroleum Geophysics," held at Texas A & M College, April 4–6, 1940.

One gathers the impression from reading these notes that the Conference was quite interesting. There are some forty-five well chosen and informative figures. Unfortunately, however, the authorities, who were responsible for the transfer of this material from the spoken lectures to the printed booklet, failed. As a result, so many errors have crept in that no student should read it until he is very well informed about practical geophysics.

The recent publication of three excellent books on practical geophysics makes it unnecessary to endeavor to point out and correct each error in this booklet. Moreover this would require a review practically as long as the original. Therefore only one typical example will be cited from each section.

Considerable space is devoted to a comparison of the torsion balance, gravimeter and pendulum. First, relative sensitivities are compared. The torsion balance measures the gravitational gradient, the unit of which (page 21) "is named for Eötvös and is 0.000,000,001 dyne per centimeter. It will be seen that the Eötvös unit is 100,000 times smaller than the milligal which is the unit used in pendulum and gravimeter work." Consequently (page 22), "it would be unscientific to compare the practical values of these instruments with the torsion balance . . . simply because the pendulum and the gravimeter must have their respective sensibilities increased at least ten thousand times which would be practically impossible." As a result (page 27), "structural features can be located with the torsion balance that could not be even suggested by the present gravimeter because the sensitivity is deficient from one hundred to one thousand times that of the torsion balance." Because they failed to comprehend this fact "certain pseudo-geophysicists were misapplying torsion balance gradients in such a way as to create the impression that after all torsion balance surveys are identical with those of of the gravimeter" (page 18), that is by constructing isogams. The seriousness of their error is made clear by a numerical example (page 25) where it is shown that a gravimeter would give 0.012 as the difference between the gravitational forces at two hypothetical points whereas from torsion balance data it can be seen that the increase in gravitational force between these two points is 0.000,549.

The pendulum is more valuable than the gravimeter because (pages 12, 19, 16) it gives the absolute value of gravity. Since (page 16) "the cost of making a survey is dependent upon the results and the financial returns," is not surprising that (page 15) "the pendulum equipment is much more costly than any other gravitational method because the investment in equipment is greater."

The magnetic section contains fewer errors than the rest, but even in it there are such statements as (page 36) "the magnetic susceptibility of a vacuum is taken as unity. All organic compounds measured have values less than unity, that is negative."

The section on temperature includes a rather confusing paragraph (page 48). "This work suggests that oil well temperatures conform to a simple law, namely, the temperature at the depth, D, is equal to the computed mean annual temperature for the area plus the product of the increase in temperature per foot and the depth in feet. However, the surface temperature can be used for all practical purposes since the temperatures used in computation can be taken at small intervals from the surface, some of which will indicate a constant temperature, independent of surface temperature changes accurate enough in the study of well temperatures in a particular area."

Most seismic prospectors would doubt that (page 52) "Seismograph work would be simplified and made more dependable if an explosion could be devised so as to produce a series, instead of an impulse, at equal intervals of time then the average velocity could be measured on the film record." Nor is it usually believed (pages 53 and 55) that first arrivals are always waves which have travelled along shallow horizontal layers.

In the section on electrical methods, methods depending on natural currents (page 60) are said to be valueless and yet those depending on natural potentials (page 62) have "very favorable possibilities." The Wenner-Gish method (page 63) "is limited as to the depth of penetration and sufficient sensitivity to differentiate between geologic strata," and consequently is of little practical value, but (page 65) the modification known as Lee's Partitioning Method "is expected to take its place as the most promising geophysical method that has been developed without exception to any other geophysical method. It is stated that (page 65) "The following is a list of accomplished facts, possible with this method, based upon actual field work.

(1) Geologic strata or beds mapped accurately by determining characteristic changes in resistivity at depths measured accurately.

(2) Geologic structure accurately mapped. In some places to 7000 ft. depth.

(3) Changes in impregnation (or related porosity) or strata mapped accurately.

(4) Faults in any kind of strata mapped directly and accurately.

(5) Gas located, depth and areal limits mapped.

(6) Salt water level determined accurately.

(7) Salt water contacts with oil, gas, fresh water, sand, shales, rocks, & etc. determined and mapped accurately.

The Lee Partitioning Method is capable of obtaining more geological information than is possible by any other geophysical method at no greater cost." It would be interesting to know more about this "actual field work."

W. M. Rust, Jr.

Strength and Structure of the Earth, by Reginald Aldworth Daly. Prentice-Hall Geology Series, New York 1940. 434+ix pp. $3.50.

For the most part, the contents of this book are not what one would expect from its title. The only part that bears directly on the subject of the title is the last one of

the twelve chapters. The remainder is devoted to the assembly of the information on which the estimation of the strength of the earth's outer crust depends. Since such estimates are based almost entirely on the degree of departure from isostasy, the book is very largely devoted to the measurements of gravity and of deflections of the vertical and their implications in terms of the shape of the earth and the degree to which topography is balanced by density variations within the crust.

It appears that Professor Daly has made a very thorough study of the original sources of the fundamental data on which the determination of the earth's strength depend and has then assembled the material into this volume. The scope of the material thus assembled is indicated by the list of special acknowledgments to institutions and authors: this includes the United States Coast & Geodetic Survey, the Canadian Dominion Observatory, the Survey of India, the Finnish Geodetic Institute, and the Baltic Geodetic Commission, and Messrs. Bowie, Cassinis, Glennie, Gutenberg, Heiskanen, Jeffreys, Jung, Lambert, Matuyama, Sauramo, Vening Meinesz, and others.

The book includes many details of gravity surveys throughout the world and their discussion in tems of different schemes of isostasy. The presentation includes a great many quotations from the acknowledgments listed above and they constitute some 20% of the total content of the book. The wide range of sources covered serves to compare the details of the various systems of isostasy which have come about through investigations by different men of data from widely different parts of the earth's surface. In particular, those who are familiar with the complete zone-by-zone isostasy of Hayford and Bowie will come to realize that this is probably far from a physical fact and is largely a fiction of mathematical convenience. A much broader system of equilibrium, which is combination of the Pratt and Airy systems of isostasy, apparently is nearer to reality. That this feeling is developed after reading the book is probably a reflection of many quotations from Heiskanen and Professor Daly's evident belief that Heiskanen's ideas, including the tri-axial ellipsoid, are the nearest current approach to a true representation of conditions in the crust.

Considerable attention is given to the variation in the isostatic anomalies depending upon the variations of the systems of isostasy on which the calculations are based and upon the form of the geoid to which the anomalies are referred. An attempt is made to reconcile some of the apparent inconsistencies in the strength requirements for the earth's shells by consideration of the different bases on which these anomalies have been computed in the past and reference of all to a more uniform system. Thus it is shown that the apparent weakness of the earth's crust and high fluidity of the underlying heavy asthenosphere, as indicated by the recovery of Fennoscandia and Labrador from the burden of the Pleistocene ice cap in contrast with the apparent strength of the crust, as indicated by the large anomalies in peninsular India, are not grossly inconsistent when both sets of anomalies are computed from the Heiskanen tri-axial ellipsoid and when consideration is given to the different areas of the anomalies in the two cases and the consequent demands upon the strength of the crust supporting them.

As a review of the gravitational tests of isostasy and collection of data from all over the world, the present book may be considered somewhat as a sequel to Bowie's *Isostasy*. However, Professor Daly's work is broader in that it gives rather careful and quite unbiased consideration to different investigators with conflicting points of view and conclusions. The almost complete absence of mathematics may appeal to the geological or general reader, but in some cases attempts to explain mathematical equations in words are either inaccurate or inadequate to the extent that they might better have

been omitted. This is particularly true with respect to the formula for gravity on the surface on the earth (p. 109) and in the use of the Clausius—Clapeyron equation (p. 412). There are a few minor quantitative inaccuracies and errors of description, particularly of pendulum apparatus (p. 112), and some places in which quotations from other writers give an incorrect impression when set out by themselves. However, Professor Daly has done a real service in bringing together a critical review of the present status of isotasy and its bearing on the strength of the earth's crust and in showing the limits to the depths and properties of the outer part of the earth which are derivable from present gravity and deflection observations.

L. L. NETTLETON

Annual Reviews of Petroleum Technology, Vol. 5 (covering 1939), published by the Institute of Petroleum, c/o the University, Edgbaston, Birmingham 15, England. 444 pp., U.S.A. $2.70 incl. postage.

It is of interest that the present volume, the fifth in the series of annual reviews of developments in the science and technology of petroleum, has been published under the stress of war conditions in England. Inevitable restrictions and voluntary censorship has led to omissions by the authors of the twenty-eight chapters comprising the volume. However, the reader will find a comprehensive review covering all phases of the industry from, regional exploration and development, drilling, production, through refining and including engine developments. During 1939 progress was probably most marked on the refining side of the industry where new processes of polymerization, alkylation, cracking and reforming rapidly developed. Thus a considerable portion of the review covers such developments.

Geophysics is covered in a brief six pages by J. H. Jones. Hence the volume is not recommended to geophysicists who are interested only in their own field. On the other hand to one interested in following the development of other phases of the industry, it provides a concise résumé of progress and modern trends presented by some forty competent reviewers. Also of interest to students of the industry are the lists of references following each chapter comprising not less than 2700 items.

R. D. WYCKOFF

PATENTS*

ELECTRICAL PROSPECTING

U.S. No. 2,217,780, T. S. West and C. C. Beacham, Iss. 10/15/40, App.. 7/26/37.

Method of Electrical Geophysical Prospecting and Apparatus for Practicing Said Method—Distribution of current through the earth is changed while recordings are made of potential differences picked up by several potential electrodes. Vacuum tube potential indicators can be set to zero deflection so that changes in potentials can be observed directly.

GRAVIMETRIC PROSPECTING

U.S. No. 2,217,123, J. D. Malmqvist, Iss. 10/8/40, Appl. 10/11/38, Assign. Bolidens Gruvaktiebolag, Sweden.

Apparatus for Determing the Alterations of the Horizontal Components of the Force of Gravity—The angle between the suspension wires of two spaced plummets is determined by measuring the electrostatic capacity between the plummets and adjoining fixed plates.

U.S. No. 2,217,361, H. M. Evjen and D. S. Muzzey Jr., Iss. 10/8/40 Appl. 5/21/38, Assign. Shell Development Company.

Gravity Measuring Instrument—A gas-spring gravimeter of the general astatized type in which the system is balanced on a knife-edge allowing it to tilt as the liquid is displaced by changes of gravity. Tilting increases the normal displacement of liquid thus increasing sensitivity. Stability may be regulated by shifting a weight to raise or lower the center of gravity.

U.S. No. 2,218,140, F. E. Wright and J. L. England, Iss. 10/15/40, Appl. 12/15/38, Assign. Carnegie Institution of Washington.

Gravity Torsion Balance—A weighted arm radially supported at the center of a horizontal helix is deflected to a definite position by rotating the helix-supporting frame a measurable amount about the helix axis to determine the force of gravity. Temperature control, compensation and indication are provided. Clamping means and level viewing means are included.

U.S. No. 2,220,199, J. L. Bible and R. H. Ray, Iss. 11/5/40, Appl. 12/27/38, Assign. Stanolind Oil and Gas Company.

Clamping Device for Force Responsive Element—Bar-type bifilar gravimeter is clamped between two pairs of faces which approach from opposite sides to clamp the bar in approximate operating position.

U.S. No. 2,221,480, G. A. Ising, Iss. 11/12/40, Appl. 2/11/38.

Gravity Measurements—The support of an astatized pendulum is periodically tilted a fixed amount while deflections are recorded. The degree of astatization is indicated by the amount of shift of the pendulum.

*Quarterly listings provided by Gary Muffly, G. R. & D. Co.

SEISMOGRAPH PROSPECTING

U.S. No. 2,215,297, J. E. Owen, Iss. 9/17/40, Appl. 2/16/40, Assign. Geophysical Research Corporation.

Seismic Surveying—Surface waves are cancelled out by combining outputs of two geophones placed at different angles with respect to vertical. Phase and magnitude of of the surface waves received are adjusted for cancellation.

U.S. No. 2,216,452, J. E. Owen, Iss. 10/1/40, Appl. 5/27/38, Assign. Geophysical Research Corporation.

Seismic Surveying—Method of cancelling surface waves by phase and amplitude adjustments of outputs of horizontal and vertical seismometers.

U.S. No. 2,217,720, J. F. Anderson, Iss. 10/15/40, Appl. 9/19/38, Assign. Sun Oil Company.

Apparatus for Solving Seismographic Problems—Reflection problems are solved with a mechanical device which locates the reflecting surfaces geometrically.

U.S. No. 2,217,806, Gary Muffly, Iss. 10/15/40, Appl. 7/29/37, Assign. Gulf Research & Development Company.

Seismograph Prospecting—Tuning of a seismograph amplifier is varied as a function of time.

U.S. No. 2,217,828, R. D. Wyckoff, Iss. 10/15/40, Appl. 7/16/37, Assign. Gulf Research & Development Company.

Seismograph Prospecting Apparatus—A heterodyne type amplifier converts seismic signals to high frequency side bands. A sharply tuned filter selects the frequencies in one side band which correspond to the desired seismic frequencies and a detector converts them back to the original low frequency. The filter frequency is fixed and identical in all channels and tuning is accomplished in all channels simultaneously by changing the frequency of the heterodyne oscillator common to all.

U.S. No. 2,219,508, L. F. Athy and E. V. McCollum, Iss. 10/29/40, Appl. 8/31/38, Assign. Continental Oil Company.

Method and Apparatus for Seismic Surveying—Seismograph reflection setups have one line or two intersecting lines of detectors offset from the shot point by a distance of 75 to 1000 feet, thus providing continuous control on the reflecting horizon but removing all detectors from the immediate vicinity of the shot and the disturbing ground-roll zone.

GEOCHEMICAL PROSPECTING

U.S. No. 2,223,183, E. B. Peck, Iss. 11/26/40, Appl. 9/2/37, Assign. Standard Oil Development Company.

Prospecting for Oil—Soil gas samples are burned and the temperature rises due to their combustion are measured. Samples showing greatest combustion effect are tested for carbon-hydrogen ratio by correlating heat of combustion with CO_2 content.

U.S. No. 2,223,785, G. L. Hassler, Iss. 12/3/40, Appl. 12/20/38, Assign. Shell Development Co.

Gas Sampling System—A container for storing gaseous mixtures designed for delivering such mixtures to and from the containers without contamination or dilution by atmospheric air or impurities. Comprises two concentric gas-tight envelopes at least the inner one being made of flexible material whereby suitable manipulation of gaseous pressure permits filling or emptying either container.

WELL LOGGING

U.S. No. 2,212,273, Oscar Martienssen, Iss. 8/20/40, Appl. 10/12/38.

Arrangement for Measuring the Local Specific Resistance of Borehole Strata—Well logging electrode consists of a heavy lead weight which will make contact with the bore wall. Weight is covered with insulating jacket except for a small central section so that contact is localized.

U.S. No. 2,212,274, Oscar Martienssen, Iss. 8/20/40, Appl. 10/21/38.

Method of Exploring the Porosity of Geologic Strata Traversed by Boreholes—Self emf's due to porosity are logged by measuring the current flow while a small D.C. potential is applied. Counter emf. from induced electro-osmotic flow causes current to decrease opposite porous formations.

U.S. No. 2,214,674, J. T. Hayward, Iss. 9/10/40, Appl. 1/29/38.

Method of Logging Wells—A well is logged during drilling by analysis of the drill mud before and after it passes through the well. Rate of mud flow, depth, etc., are observed so that a portion of the fluid entering the well can be identified after returning to the surface, and depth at which it picked up disintegrated rock may be determined. Viscosity, gas, oil or salt content, etc., of samples may be studied. Mud pressure is kept higher than formation pressure.

U.S. No. 2,214,786, B. P. Bishop, Iss. 9/17/40, Appl. 8/15/38.

Apparatus for Logging Holes while Drilling—Well is logged while being drilled by measuring self e.m.f. between uninsulated drill stem and a surface electrode.

U.S. No. 2,216,340, R. D. Elliott, Iss. 10/1/40, Appl. 6/25/37, Assign. Lane-Wells Company.

Electric Cable—Well logging cable. Each conductor has a stranded steel sheath for magnetic shielding.

U.S. No. 2,217,768, J. M. Pearson, Iss. 10/15/40, Appl. 11/5/37, Assign. Sperry-Sun Well Surveying Company.

Apparatus for Orienting Cores—A core from a well bore is tested by rotating it in the vicinity of an astatic magnetometer while recording deflections. The core is then reversed to obtain a second record which is compared to the first record to separate polarization and susceptibility effects.

U.S. No. 2,219,273, S. A. Scherbatskoy, Iss. 10/22/40, Appl. 6/16/39, Assign. Well Surveys, Inc.

Well Logging by Measurements of Radioactivity—Radioactivity well logging measurements are made with an ionization chamber whose output is commutated, ampli-

fied with an A.C. amplifier and recorded at the surface. Ionization chamber uses nitrogen under about 20 atmospheres of pressure.

U.S. No. 2,219,274, S. A. Scherbatskoy, Iss. 10/22/40, Appl. 10/16/39, Assign. Well Surveys, Inc.

Well Survey Method and Apparatus—A null method of recording wherein the D.C. output of an ionization chamber in a well is balanced out by remote control from the surface and any unbalance is indicated by means of an A.C. amplifier with commutated D.C. input.

U.S. No. 2,220,070, C. B. Aiken, Iss. 11/5/50, Appl. 3/24/36, Assign. Schlumberger Well Surveying Corp.

Method of and Apparatus for Magnetically Exploring Earth Strata—Inductive coupling between two or more coils is indicated while the coils are moved through a well in spaced relationship to log the well. Setup may be balanced or null-reading, and may indicate phase as well as amplitude. Frequency variations of an oscillator in the well may be measured at the surface.

U.S. No. 2,220,205, S. E. Buckley, Iss. 11/5/40, Appl. 3/31/39, Assign. Standard Oil Development Company.

Method of Locating Detectable Cement in a Borehole—Cement in a bore hole is located by adding radioactive material to the cement and logging the well for emitted rays.

U.S. No. 2,220,509, Folkert Brons, Iss. 11/5/40, Appl. 1/30/40, Assign. Shell Development Company.

Process and Apparatus for Exploring Geological Strata—Well is logged by passing a neutron source through it while detecting neutrons diffused by the surrounding formations. Returning neutrons disintegrate a selected element such as cadmium, and the disintegration products are detected with a Geiger counter or ionization chamber.

U.S. No. 2,220,788, R. W. Lohman, Iss. 11/5/40, Appl. 6/24/35, Assign. Schlumberger Well Surveying Corp.

Method and Apparatus for Investigating Subterranean Strata by Means of Electromagnetic Measurements—Well is logged for magnetic or inductive effects. Induction between exploring coils traversing the bore hole is studied with respect to amplitude, phase, or distortion. Earth's field may also be logged.

U.S. No. 2,221,951, W. D. Mounce and W. M. Rust, Jr., Iss. 11/19/40, Appl. 12/24/37, Assign. Standard Oil Development Company.

Making Electrical Measurements—A transformer placed near logging electrodes in a well matches the low electrode impedance to the high measuring-circuit impedance so that changing cable inductance will not affect measurements. A condenser is provided to allow simultaneous measurement of natural D.C. earth potentials.

U.S. No. 2,222,136, C. B. Bazzoni and J. Razek, Iss. 11/19/40, Appl. 8/2/38, Assign. Sperry-Sun Well Surveying Company.

Electrical Prospecting Method and Apparatus—A well logger records variations as a variable-density trace which is reproduced later in the form of a curve. Variations

may be balanced against a simultaneously recorded standard-exposure trace to cancel spurious effects of variable light source or film speed.

U.S. No. 2,222,149, E. Lipson, Iss. 11/19/40, Appl. 11/28/39, Assign. Casolog, Inc.

Method and Apparatus for Logging Wells—Electrical well logging setup uses a single well electrode and two surface electrodes connected in a bridge circuit.

U.S. No. 2,222,182, W. D. Mounce and W. M. Rust, Jr., Iss. 11/19/40, Appl. 8/21/37, Assign. Standard Oil Development Company.

Earth Impedance Measuring Device—Well logger or the like has two electrodes connected in the feedback circuit or in a tuned circuit of a vacuum tube oscillator. Changes of impedance vary the strength of oscillation which is indicated by a plate current meter at the surface.

U.S. No. 2,222,608, R. D. Elliott, Iss. 11/26/40, Appl. 5/17/37, Assign. Schlumberger Well Surveying Corp.

Electrical Surveying in Drill Holes—Electrical well-logging circuit with compensation for drift of the recording meter due to changes in electrical characteristics of the cable as it is unwound. Current and potential circuits may each use one long electrode and one short electrode. Cable shield may be used as one electrode. Shields may be used between conductors. Electrode assembly details are described and claimed.

THE SOCIETY ROUND TABLE

ANNOUNCEMENT OF ANNUAL MEETING—1941

The Annual Meeting of the Society of Exploration Geophysicists will be held at the Rice Hotel, Houston, Texas, April 1 to 3, inclusive.

TENTATIVE PROGRAM

Tuesday, April 1—A.M. Business Meeting and Technical Session.
P.M. Technical Session.
Wednesday, April 2—A.M. Technical Session.
P.M. Technical Session.
Thursday, April 3—A.M. Joint Session with A.A.P.G. and S.E.P.M. at which time the presidential addresses and other papers of general interest will be presented.
P.M. No Technical Session in order that members may hear papers of general interest on the A.A.P.G. program.

PROGRAM COMMITTEE

E. A. Eckhardt—	Atlantic Coast Area
J. A. Sharpe—	Tulsa Area
C. A. Heiland—	Rocky Mountain Area
Henry C. Cortes—	Dallas-Ft. Worth Area
Herbert Hoover, Jr.—	Pacific Coast Area
Frank Goldstone—	Houston Area
T. I. Harkins—	Houston Area
W. M. Rust, Jr.—	Houston Area
H. B. Peacock—	Houston Area (General Chairman)

IT IS URGED THAT ALL MEMBERS DESIRING TO PRESENT PAPERS NOTIFY ANY MEMBER OF THE PROGRAM COMMITTEE AS SOON AS POSSIBLE.

HOTEL ACCOMMODATIONS

About 1500 rooms have been reserved at the various hotels of the city for the combined conventions. However, it is necessary that individual reservations be made before March 20. After that date all unreserved rooms will be made available to the general public. The following hotel information is given for your convenience:

			Minimum Rates			
	No. of	*No. Blocks*	*Without Bath*		*With Bath*	
Hotel	*Rooms*	*from Rice*	*Single*	*Double*	*Single*	*Double*
Rice	1000				$2.50	$4.00
Lamar	500	5			2.50	4.00
Texas State	400	3			2.50	4.00
San Jacinto	300	3	$1.50	$2.50	2.50	4.00
Ben Milam	250	6			2.50	4.00
Sam Houston	200	3			2.50	4.00

Hotel	No. of Rooms	No. Blocks from Rice	Minimum Rates Without Bath Single	Without Bath Double	With Bath Single	With Bath Double
William Penn	175	5			2.50	4.00
Cotton	175	3			2.50	4.00
Auditorium	175	2			2.50	4.00
Warwick	153	50			2.50	4.00
De George	150	7	$2.00	$3.00	2.50	4.00
Plaza	102	50			2.50	4.00

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

Dorsey Augustus DeWoody
E. A. Eckhardt, R. D. Wyckoff, L. W. Gardner

Jardel Borges Ferreira
Herbert Hoover, Jr., Wayne H. Denning (Article III-C-1)

Holloway Halstead Frost
L. M. Mott-Smith, E. V. McCollum, G. P. Wilson

A B Hamil
O. S. Petty, R. B. Pratt, W. Harlan Taylor

John Brackett Hersey
Maurice Ewing, W. B. Agocs (Article III-C-1)

Paul Hugh Jeffers
Arland I. Innes, Andrew Gilmour, L. Y. Faust

Lewis Owen Kelsey
W. R. Ransone, Earl Thomas, C. V. A. Pittman

Noyes Darling Smith
J. P. Woods, H. M. Evjen, D. S. Muzzey, Jr.

Richard Hanawalt Tallman
A. B. Bryan, George E. Wagoner, Robert L. Craig

Garvin Lawrence Taylor
Daniel Silverman, Joseph A. Sharpe, R. Clare Coffin

Eugene England Wilson
James L. Morris, W. H. Schley, W. W. Newton

ASSOCIATE

Charles Carpenter Bates
George E. Wagoner, A. B. Bryan, R. W. Gemmer

Horace Chesterfield Davis
G. R. Brotherhood, Ray K. Carter (Article III-C-1)

Burleson Graham
R. A. Pratt, R. A. Weisbrich, T. L. Allen
C. Russell Hale
Wayne H. Denning, A. M. Eichelberger, Jr., Herbert Hoover, Jr.
Gerald Willis Hostetler
T. L. Allen, John F. Imle, W. O. Bazhaw
John Byron Jones
G. F. Kaufmann, C. A. Heiland (Article III-C-1)
Lynn Alton Smitherman
W. Lee Moore, W. O. Bazhaw, T. L. Allen
Charles Everett Thompson
W. O. Bazhaw, R. B. Pratt, R. A. Weisbrich
Wilber H. Young, Jr.
Sylvain Pirson, W. R. Ransone, Ray K. Carter

TRANSFER TO ACTIVE
(Executive Order G-11)

Willis Oliver Bazhaw
James Dungan Berwick
Raiford H. Burton
James Edward Gunn
E. Darrell Williams

The ballot reprinted below was mailed all active members of the Society of Exploration Geophysicists on December 15, 1940. Active members who failed to receive ballots may secure them by notifying J. F. Gallie, Business Manager, P. O. Box 777, Austin, Texas. *Only active members who have paid 1941 dues are eligible to vote.*

OFFICIAL BALLOT

FOR THE YEAR MARCH, 1941—MARCH, 1942
For the Election of Officers for the
SOCIETY OF EXPLORATION GEOPHYSICISTS

FOR PRESIDENT
Vote Once Only

H. B. PEACOCK	☐
ROLAND F. BEERS	☐
_____	☐

FOR VICE-PRESIDENT
Vote Once Only

FRANK GOLDSTONE	☐
HENRY SALVATORI	☐
_____	☐

FOR SECRETARY-TREASURER
Vote Once Only

WILLIAM M. RUST, JR.	☐
JOSEPH A. SHARPE	☐
_____	☐

FOR EDITOR
Vote Once Only

RICHARD L. DOAN	☐
R. D. WYCKOFF	☐
_____	☐

After voting, place in accompanying official envelope, which should then be signed and mailed to the

SECRETARY-TREASURER,
ANDREW GILMOUR
P. O. Box 2040
Tulsa, Oklahoma

PERSONAL ITEMS

H. W. STRALEY III, has the distinction of having placed all of his senior class (June, 1940) in permanent positions within the profession by July 1 and his entire junior (June, 1941) class in temporary summer employment. The enrollment in the department of geology at Baylor has increased 39% since Mr. Straley assumed its direction, and the number of B.S. majors has doubled.

Advice has been received that WARREN A. ALEXANDER is now in Ploesti, Roumania, with Romano-Americana.

HOWARD L. COBB, newly-elected member, may be addressed at Box 491, Hanover, New Hampshire. He is in attendance at Dartmouth College.

GEORG MARKSTEIN is no longer connected with Compania de Petroleo Shell de Colombia. He should be addressed at Calle 35, No. 17/21, Bogota, Colombia.

GIFFORD E. WHITE has advised the Society of his new address—273 Beacon Street, Boston, Massachusetts.

HENRY SCHOELLHORN III, a recent graduate of the Colorado School of Mines, has accepted employment with the Gulf Research and Development Company. He may be addressed c/o Seismic Party #20, P. O. Drawer 552, Liberty, Texas.

C. T. MACALLISTER is now with the Independent Exploration Company, 2011 Esperson Building, Houston, Texas.

MALVIN G. HOFFMAN, whose "Structural History of Billings Field, Noble County, Oklahoma, Interpreted in Terms of Isostasy" appeared in the November *A.A.P.G. Bulletin*, is geologist with Geochemical Service Corporation, 321 S. Detroit, Tulsa, Oklahoma.

The Petroleum Engineer has announced the election of the following officers: W.L. LOVE, President; K. C. SCLATER, First Vice-President and Editor; T. J. CROWLEY, Vice-President and Advertising Manager; and W. T. Bryan, General Manager and Secretary-Treasurer.

ROY LEE GALLAWAY, recently returned from work in Egypt, and employed by the Texas Company, is temporarily located in Alexandria, Louisiana.

T. C. RICHARDS, in Burma for some time past, has returned to England, where he may be addressed at 104, Archery Road, Eltham, London.

FRANCIS H. CADY, of the Carter Oil Company, is in Aberdeen, Mississippi, with his postal address being Box 252.

GARDNER P. WILSON, Junior Detailer with the Lockheed Aircraft Corporation of Burbank, California, is located at 946 N. Catalina in that city.

VINCENT EMANUEL, in Italy for the past few months, is returning shortly to the United States.

R. G. PATERSON, recently-elected member, is a Lieutenant with the R. C. N. V. R. and may be reached through the Fleet Mail Office, Halifax, Nova Scotia, Canada.

WILLIAM B. AGOCS has left the employ of the Gulf Research and Development Company to do graduate study in Physics at Lehigh University. His address is 940 Broadway, Bethlehem, Pennsylvania.

The Jackson, Mississippi, office of Geophysical Service, Inc., has been moved to 207 100 East Pearl Building, EWIN D. GABY reports.

FRANK F. LEHMAN is working in Barcelona, Venezuela, for the Mene Grande Oil Company, Apartado 45.

F. H. AGEE may be addressed at P. O. Box 413, Longview, Texas.

H. RUTHERFORD is now located in Centralia, Illinois, where his mailing address is P. O. Box 96.

RAY K. CARTER has returned from South America to his position with Geophysical Service, Inc., 1311 Republic Bank Building, Dallas, Texas.

E. W. FISHER is serving as an Electrical Engineer with the War Department. His local address is 200 Courtland Avenue, Topeka, Kansas.

PAUL H. BOOTS is employed by the Mene Grande Oil Company, Seismograph Division, Apartado 45, Barcelona, Venezuela.

E. R. SELBY has accepted employment as an Engineer with the Magnetest Corporation, 3504 Atlantic Avenue, Long Beach, California.

EDGAR J. STULKEN is acting as an Instructor in Mathematics at Allen Academy, Bryan, Texas.

T. DE PIJPER has left Burma for Pangkalan Brandan, Sumatra, where he is working for N. V. Bataafsche Petroleum Maatschappij.

W. B. WILEY, of the Gulf Research and Development Company, has been transferred from Watonga, Oklahoma, to Columbia, Mississippi.

A. A. HOTARD is located in Houma, Louisiana, at 352 Ruth Street.

A. N. EBY, of the Superior Oil and Gas Company, is temporarily located in Columbus, Texas.

J. W. THOMAS, JR., of the Stanolind Oil and Gas Company, has been transferred from Canadian, Texas, to Garden City, Kansas.

L. W. BLAU, J. P. SCHUMACHER, PAUL WEAVER, FREDERICK ROMBERG, W. O. BAZHAW, J. BRIAN EBY, F. W. ROLSHAUSEN, E. DE GOLYER, R. B. COIT, F. JULIUS FOHS, BRUCE H. HARLTON, CHAS. GILL MORGAN, H. W. STRALEY III, JOSIAH TAYLOR, LEO W. KONZ, C. V. A. PITTMAN, and MARION J. MOORE were among Society members attending the 53rd Annual Meeting of the Geological Society of America, which was held December 26–28 in Austin, Texas.

ROBERT G. NISLE is now associated with the Dictograph Sales Corporation, 408 West Building, Houston, Texas, as Telephone Engineer.

R. B. COIT, of Geophysical Service, Inc., has returned to the United States from the Netherlands East Indies.

DWIGHT E. WARD, of the Carter Oil Company, has been transferred from Philadelphia, Mississippi, to Phillipsburg, Kansas, where his postal address is Box C.

GEORGE B. KAISER is now serving as a Captain at Fort Monmouth, Red Bank, New Jersey.

HOMER ROBERTS, of the Petty Geophysical Engineering Company, has returned from Burma to San Antonio, Texas.

R. A. WATSON, of the National Geophysical Company, has been transferred from Alexandria to Winnfield, Louisiana, with the postal address Box 407.

J. C. HOFFMAN, of the United Geophysical Company, is located at 317 Haberfelde Building, Bakersfield, California.

NEIL W. MANN, of Geophysical Service, Inc., has returned from Bahrein Island to Dallas, Texas.

SHERWIN F. KELLY, who recently gave several lectures and field demonstrations in exploration geophysics to students of the Montana School of Mines in Butte, has been named Walker-Ames Lecturer in Geophysics at the University of Washington in Seattle. During his visiting lectureship he will give eight lectures on the subject, emphasizing the practical importance of the geophysical sciences and the interrelationship with geology.

STATEMENT OF THE OWNERSHIP, MANAGEMENT, CIRCULATION, ETC., REQUIRED BY THE ACTS OF CONGRESS OF AUGUST 24, 1912, AND MARCH 3, 1933

of GEOPHYSICS, published quarterly at Menasha, Wisconsin, for October 1940.

State of Texas }
County of Travis } ss.

Before me, a Notary Public in and for the State and county aforesaid, personally appeared J. F. Gallie, who, having been duly sworn according to law, deposes and says that he is the Business Manager of the Geophysics and that the following is, to the best of his knowledge and belief, a true statement of the ownership, management (and if a daily paper, the circulation), etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in section 537, Postal Laws and Regulations, printed on the reverse of this form, to wit:

1. That the names and addresses of the publisher, editor, managing editor, and business managers are Publisher, George Banta Publishing Company, Menasha, Wisconsin; Editor, R. D. Wyckoff, Box 2038, Pittsburgh, Pennsylvania; Managing Editor, R. D. Wyckoff, Box 2038, Pittsburgh, Pennsylvania; Business Manager, J. F. Gallie, Box 777, Austin, Texas.

2. That the owner is (If owned by a corporation, its name and address must be stated and also immediately thereunder the names and addresses of stockholders owning or holding one per cent or more of total amount of stock. If not owned by a corporation, the names and addresses of the individual owners must be given. If owned by a firm, company, or other unincorporated concern its name and address, as well as those of each individual member, must be given.) Owned by The Society of Exploration Geophysicists, Executive Committee: R. D. Wyckoff, Editor, Box 2038, Pittsburgh, Pa.; J. F. Gallie, Business Manager, Box 777, Austin Texas; W. T. Born, President, Box 2040, Tulsa, Oklahoma; H. B. Peacock, Vice-President, Houston, Texas; Andrew Gilmore, Secretary-Treasurer, Tulsa, Oklahoma; E. A. Eckhardt, Past-President, Box 2038, Pittsburgh, Pennsylvania.

3. That the known bondholders, mortgagees, and other security holders owning or holding 1 per cent or more of total amount of bonds, mortgages, or other securities are: (If there are none, so state.) None; non-profit organization.

4. That the two paragraphs next above, giving the names of the owners, stockholders, and security holders, if any, contain not only the list of stockholders and security holders as they appear upon the books of the company but also, in cases where the stockholder or security holder appears upon the books of the company as trustee or in any other fiduciary relation, the name of the person or corporation for whom such trustee is acting, is given; also that the said two paragraphs contain statements embracing affiant's full knowledge and belief as to the circumstances and conditions under which stockholders and security holders who do not appear upon the books of the company as trustees, hold stock and securities in a capacity other than that of a bona fide owner; and this affiant has no reason to believe that any other person, association, or corporation has any interest direct or indirect in the said stock, bonds, or other securities than as so stated by him.

5. That the average number of copies of each issue of this publication sold or distributed, through the mails or otherwise, to paid subscribers during the twelve months preceding the date shown above is not daily. (This information is required from daily publications only.)

J. F. GALLIE

Sworn to and subscribed before me this 18th day of November 1940.

[SEAL] ANNE W. GREEN

(My commission expires June 1, 1941.)